Mould Resistance of Full Scale Wood Frame Wall Assemblies

by

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Abstract

Mould Resistance of Full Scale Wood Frame Wall Assemblies

The primary objective of this study was to investigate mould growth resistance of different types of wood products which include the sheathing and framing within full scale wall assemblies. Secondary objectives were to investigate the difference in mould growth resistance between borate-treated and untreated wood products as well as provide information about mould growth under different temperature and humidity conditions for treated and untreated wood products.

The objective of the study is to better understand mould growth, and to examine the effects of varying high moisture conditions on wooden products and the mould growth which may result. More importantly this will be examined on full scale wall assemblies; to date mould growth studies have only been performed within a laboratory on small samples of materials. Moreover, this study recreates the conditions which evidently cause mould growth on full scale wall assemblies. Tests were performed within a climate chamber on three full scale wall assemblies. The original scope of this study included an examination of the sheathing and framing components within a full scale wall assembly, however this study will focus mainly on the sheathing.

Results of this study indicate that the relative humidity conditions needed for mould growth on wood are higher than originally believed (i.e., significantly greater than 80%RH). During the first eight weeks of test number one the relative humidity at the surface of the sheathing was held constant at 95% and little mould growth was observed on the untreated sheathing (mould growth index of 3 or less); little or no mould growth on the treated sheathing (mould growth index of 1 or less). The second and third tests demonstrated that the presence of liquid water greatly accelerated the time to germinations, the amount of mould growth (up to a mould growth index of 6), and the rate of mould growth. All three tests clearly showed that borate-treatment reduced the amount of mould growth; however, the concentration of borate-treatment, and the types of materials treated, does affect the resistance of mould growth. Furthermore, there was some evidence to suggest Borate treatments of the plywood increased the time to germination significantly, from a few weeks to 16 weeks in this study, but once mould growth was initiated, the rate of mould growth was similar to that of the untreated plywood. Two mathematical models to determine mould growth were examined: Viitanen and WUFIBIO (Sedlbauer). Viitanen's model predicted time to germination and rate of growth rate well for untreated plywood, and WUFIBIO predicted time to germination but not the growth rate. It was also found both models err on the side of caution in predicting mould growth.

Recommendations include improvements to the test method and producers, and for future work.

Acknowledgements

I would like to take this opportunity to thank the many people that made this thesis and experimental work possible.

Firstly, I would like to thank my supervisor Dr. John Straube. Without his fourth year class (CivE 507), his guidance, and support, I would never have pursued a career in Building Science. His dedication and enthusiasm for the world of Building Science and his belief that the world can be changed is awe inspiring.

I would like to thank all the members of the Building Engineering Group (BEG) who have helped with all aspects of this thesis from the experimental work, to the completion of my thesis.

I would like to thank U.S. Borax Inc. for their financial support.

Finally, I would like to thank my friends, family, and my future wife Diana without them this would have been a much more difficult and arduous three years.

Dedication

I dedicate this study to the memory of my Grandfather White, the greatest engineer in my life, who instilled the belief that no dream is too big, and no challenge is too difficult.

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1 Introduction

1.1 Background

Most North Americans spend more than 90% of their natural lives indoors and the environment within those buildings affects the occupants health, quality of life, and productivity (Laporte et al 2005). Some buildings have problems with indoor air quality (IAQ) the term used to describe the health and comfort of the air inside the building. The IAQ of a building can be compromised by airborne microbial contaminants such as mould, bacteria, chemicals, or allergens. Poor IAQ has been found to affect the health and productivity of the occupants; this negative effect has been referred to as "Sick Building Syndrome" or "Building-Related Illness". According to the US Environmental Protection Agency (EPA) and the World Health Organization Experts, 30% of new or renovated homes have indoor air quality problems (United States Environmental Protection Agency 1995) and according to Occupational Safety & Health Administration (OSHA) 20% to 30% of office building are "sick" (Occupational Safety and Health Administration 1994).

Fungal growth within the indoor environment has become a major concern and a highly publicized topic. Billions of dollars are being spent on mould-related repairs and litigation costs resulting in thousands of mould related lawsuits pending in the US court system. The issues which mould imposes are not new to the last century but have existed through human history. Mould problems were written about as long ago as biblical times. In the Bible (Bible: Old Testament) the purification of people with skin disease caused by mould was noted and subsequently it was ordered that the affected clothing should be burned and the affected building materials be removed. Mould not only affects issues in building construction and indoor air quality (IAQ) but it also medical and public health, and agriculture fields, and has even influenced human history. For example the "Irish Potato Famine" devastated the Irish population killing between half a million and million Irish and caused a mass exodus from Ireland. Therefore, by making an effort to prevent, limit, or control mould growth has its obvious benefits. Mould does have some beneficial applications such as fermentation of alcohol and the production of medicine. However, the intent of this report is not to examine these uses.

1.2 Objectives

The primary objective of this study was to investigate mould growth resistance with different types of wood products which include the sheathing and framing within full scale wall assemblies. Secondary objectives included the investigation of the difference in mould growth resistance between borate-treated and untreated wood products as well as providing information about mould growth under different temperature and humidity conditions for both treated and untreated wood products.

1.3 Scope

The scope of the study was limited to the better understanding of mould growth, and to examine the effects of varying high moisture conditions on wooden products and the mould growth which may result. The study focused on oriented stand board (OSB) and plywood sheathing with and without Borate treatment. More importantly this was examined on full scale wall assemblies. The original scope of this study included an examination of the sheathing and framing components within a full scale wall assembly. However, due to the results obtained the study will focus mainly on the sheathing.

1.4 Approach

A review of the mould organism including factors which affect its growth, reasons to control mould (including health effects), and means of controlling mould growth are discussed within Chapter 2. Chapter 3 reviews past research in the area of mould growth including material testing and mathematical models. Chapter 4 discusses moisture physics and material properties. Chapters 2 through 4 provide context for later discussion. The remaining chapters describe the study and its results in some detail. Chapter 5 examines the objective, scope, and approach of the experiment, along with the conditions which the climate chamber imposed on the test wall panels. Chapter 6 examines the experimental setup including the climate chamber design, wall panel design, instrumentation selection and arrangement, and methods of documenting the progress of mould growth. Chapter 7 details the experimental data collected from all three tests. Chapter 8 examines the mould growth observed and draws conclusions from the collected data. Finally Chapter 9 and Chapter 10 review the knowledge gained through this study and discuss possible future work.

2 Mould

2.1 Fungi versus Mould

Originally fungus was classified as part of the plant kingdom, however, fungus are not true plants because they are heterotroph. Heterotrophic species, like fungus, do not produce carbon through photosynthesis but obtain carbon from organic compounds. Therefore, fungi are more closely related to the animal kingdom than the plant kingdom. However, fungi was given it own kingdom because unlike animals, fungi absorb their food rather than ingest it, and their cells are surrounded by cell walls and not cell membranes.

It has been estimated that over 1.5 million species of fungus exist, and to date mycologists have only identified 60,000 of which only 400 have been proven to cause disease in humans or animals (Ontario Association of Architects 2003). The fungi kingdom is broken into five divisions which are based upon its sexual reproductive structure; these divisions are as follows:

1. Chytridiomycota
2. Zygomycota
3. Glomeromycota
4. Ascomycota
5. Basidiomycota

Mould, or mold (American English), fall into two of the above mentioned divisions; Zygomycota, and Ascomycota. Simply put mould is division of fungi, because mould is classified as belonging to the fungi kingdom.

2.2 Factors Affecting Fungal Growth

Fungi have been around for billions of years evolving into very effective organisms which can be found in every corner of this world. Certain fungi species grow best in low relative humidity conditions at low temperature levels while others grow best in high moisture conditions at high temperatures. However, the mould examined in this thesis, which mostly occurs in buildings and may be dangerous to the health of the occupants, grows best under high moisture and warm temperature conditions.

Oxygen, spores, temperature, nutrients and moisture illustrated in Figure 2-1 are all necessary for mould growth. These requirements will be discussed in turn below.

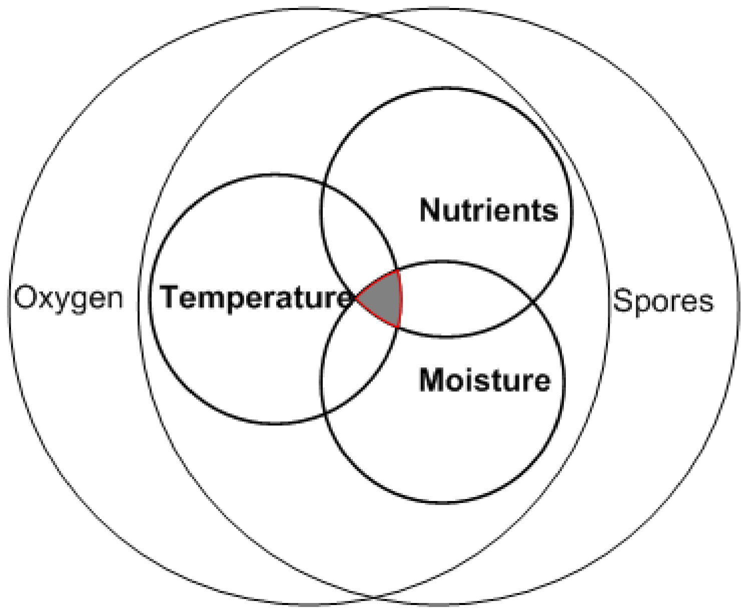

Figure 2-1: Mould Growth Requirements (Ontario Association of Architects 2003)

2.2.1 Oxygen

Oxygen is required for fungal growth, and is abundant regardless of design. For most practical applications the sealing of wall and roof spaces to reduce the amount of oxygen will not reduce oxygen levels enough to affect mould growth. In the event of a flood, mould growth will not occur underwater because of a lack of oxygen. However, mould growth will commence once the flood recedes, given other favourable conditions.

2.2.2 Spores

As mould spores exist in the outdoor air in signification concentrations and given the resiliency of mould, it should be assumed that mould spores can be found in essentially all indoor environments, within all building assemblies and on all building materials. The type of mould which is hazardous to the health of the occupants is not usually the same type of mould found in the outdoor environment. Furthermore, the mould airborne spore count within an unhealthy building is usually higher than that of the exterior environment. However, the previous statement may not always be true because in wet conditions mould does not produce as many spores, and exterior air mould spore counts can be very high in some seasons and some environments.

2.2.3 Temperature

Like most organisms mould growth is dependent upon temperature. Ideal temperature conditions for most mould species range between 20°C and 35°C. For most moulds, the growth rate outside of this range is much slower and below 5°C and above 50°C very little mould growth occurs. Outside of these ranges the mould becomes dormant, and is able to wait for long periods of time until conditions become favourable again. (Ontario Association of Architects 2003)

2.2.4 Nutrients

In most buildings the nutrients which support mould are readily available, as most building materials are organic or are produced from organic products, such as: paper, glue, paints, textiles, ceiling title, furniture, and many others. Inorganic building materials such as ceramic tile, steel, brick, and concrete can still support mould growth because they collect airborne dust which subsequently supports mould growth; thus mould can grow on virtually any substrate.

The foods which most moulds absorb are based upon carbon and nitrogen with a smaller amount of other micronutrients. Most mould prefers to collect their food through the absorption of sugar and starches. However, moulds which favour buildings are able to breakdown and absorb some of the most complex cellulose and lignin sources found in wood and derived products. Starch is cellulose which has already been broken down into a simplified form which is easier for mould to eat. Therefore, the more processed an organic material is the more likely it is to support mould growth. Furthermore, products which are porous usually support a higher mould growth because there is more surface area. For these reasons it is easy to understand why highly processed paper facing on the gypsum wall board and the very porous gypsum ceiling tiles are so susceptible to mould growth. Hence, although mould can grow by feeding on dirt and dust on inorganic materials, the rate and severity of growth is severely limited. In practice porous and processed wood products such as paper and fibreboard exhibit the fastest and most dangerous growth. Mould growth on plywood and OSB is less significant but can be a concern.

2.2.5 Moisture

As previously mentioned, the digestion process for fungi occurs outside of their bodies: they excrete the enzymes which break down their food. In order for the digestion progress to occur a certain amount of moisture is required on the substrate being consumed. This moisture may be present from built in moisture within the substrate, high relative humidity, rain, surface water or ground water.

When examining the relative humidity within a room to determine the possibility of mould growth it is important to understand that the relative humidity at the surface of the substrate may be different than that of the room. Furthermore, one of the most contested numbers within the building industry is the minimum required surface relative humidity / water activity required for mould growth. It has typically been assumed that a water activity of at least 0.80 (Hens 2000) is required for mould growth. Water activity is often used by biologists to measure the moisture conditions for mould growth. Water activity (a_w) is defined at the equilibrium relative humidity at the surface of a material divided by 100%. Hence, it is given as a decimal whereas relative humidity is given as a percentage. Moreover, according to the OAA Mould Control Practice Guide the ability for a substrate to quickly dry may be as important as avoiding wetting (Ontario Association of Architects 2003), as short term wetting does not provide sufficient time for spore germination.

2.2.6 Other Factors

Additional factors which affect mould growth include the pH of the substrate because most fungi require the substrate to stay within the range of 5 to 8 (Ontario Association of Architects 2003). However, fungi do not require sunlight as mould does not use photosynthesis to obtain its carbon, instead it has been found that exposing mould to ultraviolet radiation slows down the growth of fungi and if given a high enough intensity of radiation, the fungi may even be killed.

2.2.7 Discussion on Mould

Mould is usually attributed to water problems, and by removing the water one removes the possibility of mould growth. In addition, mould growth may be prevented if, following exposure to moisture, the source of moisture is removed and the material is immediately dried. These simple statements are true and if followed there would never be a mould problem but in reality, following these steps are not always possible. For locations which may be exposed to high moisture conditions and temperatures conducive to mould growth a suggested alternative is to remove the organic substrate or at least make it an unappealing nutrients source to the mould, preventing the mould from growing. Examining this method of mould growth prevention is one the secondary goals of this study, which is to determine if borate treatments makes the substrate unfavourable for mould growth, providing the designer with an alternative to help prevent mould growth.

Mould will not grow until a spore germinates. Once it germinates it will grow at a rate dependent on temperature, moisture, and food availability. If any of these become unfavourable, growth will slow, or even stop (become dormant). When conditions become favourable growth can resume. If the mould growth flourishes and is then stressed, a mould colony will germinate a large number of spores in the hope of finding better conditions elsewhere, and may release mycotoxins as a defence. Figure 2-2 and Figure 2-3 are found below which further illustrate the relationships between the factors discussed above (Temperature, Nutrients, and Moisture).

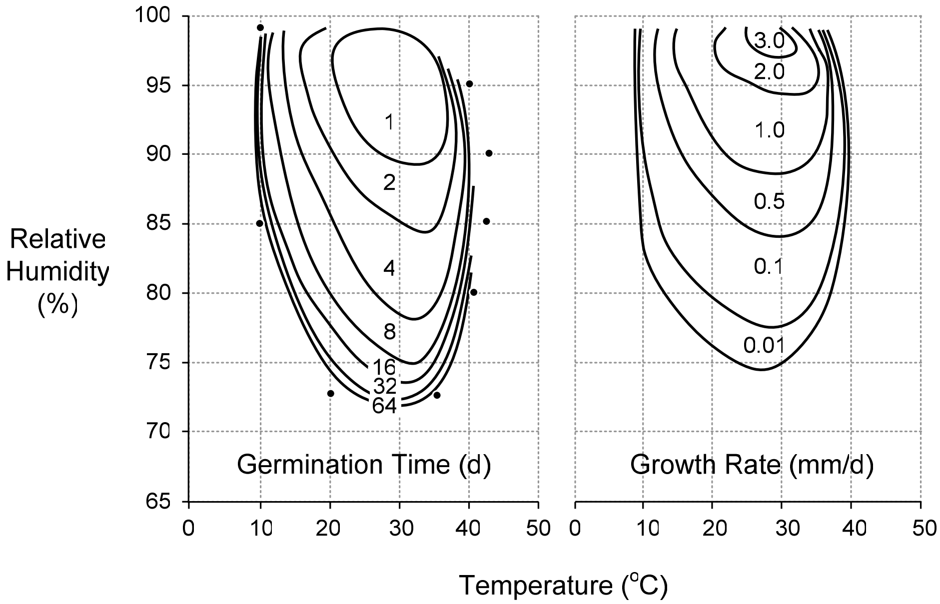

Figure 2-2: Relationship between Relative Humidity, Temperature, Germination Time and Growth Rate for Aspergillus Mould Spore (Sedlbauer 2001)

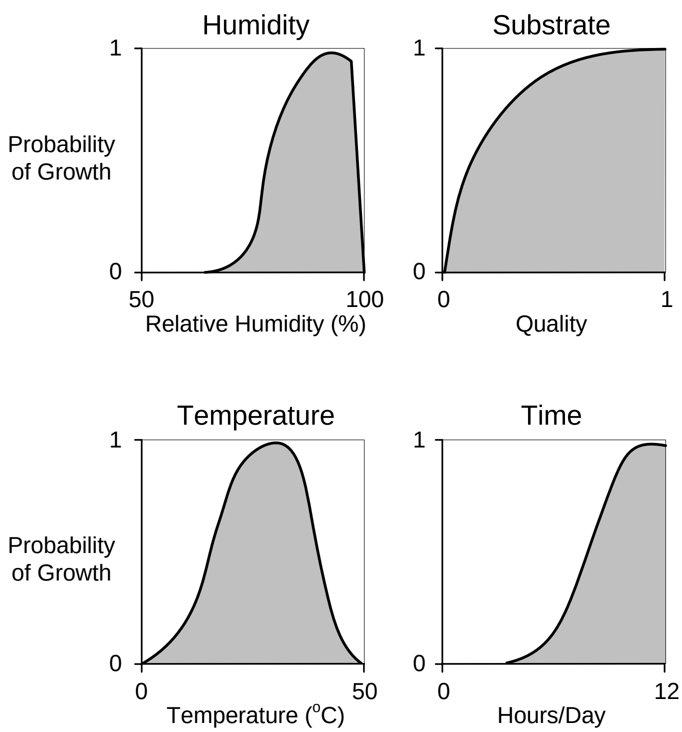

Figure 2-3: Relationships between Relative Humidity, Substrate, Temperature, and Time (Sedlbauer 2001)

2.3 Reasons to Control Mould

Mould growth should be controlled to control staining, odours and, decay, as well as to prevent adverse health effects. Decay fungi will attack wood and wood products given the right conditions (high moisture conditions and a sufficient nutrients source). In cases where these wood products are structural, decay fungi may even comprise the safety of the structure. Staining is a common by-product of mould growth and may remain after the mould has been destroyed. Volatile organic compounds (VOC) and mould spores are the reasons for odours and also may lead to unfavourable health effects.

2.3.1 Health Effects

Despite the many reasons to control mould, the negative health effects attributed to mould have received the most publicity and these effects of mould are the most complex and least understood. Some of the health effects mould has been linked to include respiratory problems, headaches, skin irritation, and flu-like symptoms (coughing, runny nose, and sore throats). It is suspected that the health effects caused by mould are a result of mould spores, mycotoxins, synergizers (which exacerbate the effect of mycotoxins), and volatile organic compounds.

Despite the common misconception from the general public, most moulds are not poisonous or "toxic". However, mould growth within buildings is often treated as "toxic" because most often there is a mix of species, therefore, ensuring that mould growth does not contain toxins growth is not typically possible. Hence, it is common practice that if mould can be smelled or seen the mould should be removed immediately. Erring on the side of caution Health Canada made the following recommendation after a review of medial literature up to 2001 (Health Canada 2004).

> "Consistent with the 1995 report, this updated review of health effects indicates that living or working in a building with material mold damage is harmful to health. Therefore, indoor mold growth in buildings should be prevented by appropriate control of moisture sources and by timely remediation of water damages. Mold growing in buildings should also be removed under safe conditions using established remediation protocols."

2.3.1.1 Mould Spores

Mould spores vary in size from 3 to 60 μm and can remain fertile for many years. Some mould spores such as those from Aspergillus and Penicillium have been known to remain viable for over 12 years (McCrady 1999). A mould growth can produce millions of spores and the amount of spores released depends on number of different conditions. The first is the type of mould and relative humidity conditions the mould growth is located within. It has also been observed that when the relative humidity changes additional mould spores may be released. Additional disturbances to mould such as foot traffic, vacuuming, cleaning products and ventilation have been known to increase the number of spores released into the indoor environment. Health effects of the mould spores include the irritation of the respiratory track and may cause allergic reactions. Figure 2-4 is a photograph of an Aspergillus Versicolor mould spore.

Figure 2-4: Aspergillus Versicolor Spore (Health Canada 2004)

2.3.2 Mycotoxins

Mycotoxins are the toxins produced by mould, however, not all types of mould produce mycotoxins. For mould to produce mycotoxins certain moisture and temperature conditions are required. The conditions required to produce mycotoxins are not currently well understood. Of those moulds which produce mycotoxins, some might only produce one type of toxin (Aspergillus) whereas others produce many different types (Penicillium produces over a 100 different types of toxins) (McCrady 1999). Mycotoxins are one of the major concerns of the public especially after a number of multi-million dollars settlements which occurred in the later 1990s. Major types of mycotoxins include Aflatoxins, Ochratoxin, Patulin, and Fusarium toxins. Mycotoxins have been known to lower the immune system response and may cause neurological damage. Some moulds produce synergizers in addition to the toxin. Synergizers exacerbated the toxic effects of some mycotoxins.

2.3.2.1 Volatile Organic Compounds

The health effects of Volatile Organic Compounds (VOC), and the required exposure level and duration, for the health effects are not agreed upon within the medical community. It is generally believed that VOCs are only irritants and that exposure to VOCs alone is not likely to cause health problems.

2.3.2.2 Allergies

An allergy is an immune malfunction whereby an individual's body overreacts to a stimulus incorrectly identified as a health threat. There are a number of signs and symptoms of allergic reaction which can include swelling, itchy red eyes, sore throat, rashes, and for some individual's asthma and breathing difficulties. For some individuals who are susceptible to developing allergies, mould can be a problem. Unfortunately, just as for many of the other mould health effects we do not know the amount of exposure required to develop an allergic response, although this does vary with the individual. What is known is that once an allergic response in an individual is developed very little exposure is required to develop the same response on subsequent exposure (Lstiburek 2002).

2.3.2.3 Discussion of Health Effects

As previously mentioned the health effects of mould are not very well understood. However, it is believed that there are five major factors which determine the health impact of mould.

1. Type of Mould
2. Size of Mould Growth
3. Duration of Exposure
4. Susceptibility of Occupants to the Health Impact of Mould
5. Location of Mould

The type of mould is critical factor in determining its impact on ones health. However, it is extremely difficult to determine the extent of that impact. Currently the technology to determine if there is "toxic" mould in your blood or tissue does not exist, making it difficult to determine its affects on ones health. What is known is that the type of mould is a major factor to the possible health impact to humans and animals. It's generally agreed that the greater the size of the mould growth the greater the health impact. What we do not know is if a short exposure to a lot of mould is worse than a prolonged exposure to a small amount of mould. It is clear some individuals are more susceptible to mould than others. For example when occupants of a building are exposed to mould, some individuals under the same exposure remain unaffected whereas the health of others is affected negatively. The location of the mould and the method of its delivery to the occupants is also very important. For example if the mould is within the wall cavity essentially isolated behind an air barrier it may have less impact on the occupants than if the mould is being delivered to the occupants via the HVAC system. Despite all the uncertainties and unknowns which are associated with mould, it is clear that reducing exposure to mould is desirable.

2.4 Controlling Mould Growth

As previously stated controlling mould growth is as simple as removing the water source or removing its source of food. Controlling mould by removing the water source is an extension of the already excepted practice of moisture control. Some of the important methods in moisture control are the use of well designed enclosures with proper detailing, the regulation of temperature and humidity within a building, the maintenance of the plumbing and HVAC system, and the selection of appropriate materials. The selection of appropriate materials also can be used to prevent feeding the mould. There are a number of different products available which replace the organic compound(s) with one that does not support mould growth. Another method for preventing mould growth on products composed of organic compounds is to make the organic compounds unappealing to mould. This can be accomplished through treatments/preservatives. Although preservatives are primarily intended to control decay fungi, they also tend to limit mould growth. Within the following section different types of wood preservatives used in Canada will be examined.

2.4.1 Wood Preservative Types

2.4.1.1 Chromate Copper Arsenate

Chromate Copper Arsenate (CCA) was once one of the most commonly used preservatives. As of January 1, 2004 the Health Canada's Pest Management Regulatory Agency has requested that CCA not to be used in most residential applications. However, CCA will continue to be used to treat wood for industrial, commercial, agricultural applications, and a few residential applications. CCA is applied to wood in a water solution under pressure which forms an insoluble precipitate through a chemical reaction called fixation. After this process the wood should be left to season to dry the wood, and remove the odour. This process turns the wood a light green colour. Composite products such as OSB undergo a different process in which the preservatives are added during the manufacturing process.

2.4.1.2 Alkaline Copper Quaternary (ACQ) and Copper Azole (CA)

Alkaline Copper Quaternary (ACQ) and Copper Azole (CA) are alternatives to CCA with the majority of the formulation being copper with additional biocides to prevent copper tolerant fungi. ACQ and CA are also applied water soluble solution and are left to season in a similar manor as CCA.

2.4.1.3 Borate

Borate has only recently been introduced to Canada as a wood preservative. It is odourless, colourless, and able to penetrate deep within green lumber (wet lumber). However, borate treated wood can only be used in areas which are protected from direct water exposure. Examining borate as a preservative is one of the objectives of this study. As a result, a more in depth description of borate was undertaken within this section.

Borates are naturally occurring salts which result from the combination of oxygen and boron. "Borate" is a general term given to compounds composed of the borate ion, BO_3^{-3}. Boron is a trivalent metallic element which does not exist in elemental form in nature, but as an oxide. Boron can be found in various oxides such as Boron Oxide (B_2O_3), Borax or sodium tetraborate decahydrate ($Na_2B_4O_7 \cdot 10H_2O$), or boric acid or orthoboric acid $B(OH)_3$. Borate salts are mined in mineral deposits found around the world including Death Valley, California and the Atacama Desert in Chile.

Borates are chosen for their low toxicity and are used in many house hold products such as detergents, cosmetics, ceramics, medicines and dozens of other common products. The average daily intake of boron is estimated to be 1-2 mg of boron per day per adult which is ingested through of food and water (Li 2005). Exposure to extremely high levels of borates can cause toxicity (5-20 grams of boric acid orally ingested) (Li 2005). The LD_{50}'s (Lethal dose which causes the death of 50% of a group of test animals.) of borates ranges from 2550 mg/kg for disodium octaborate tetrahydrate (DSOT) to 6000 mg/kg for borax (Li 2005). As stated above, borates are consider having a low toxicity and it is estimated that the use of borates as preservatives in building materials will have minimal skin contact with the occupants given the most likely location of materials to be enclosed within the wall assembly. Furthermore, a life cycle analysis found that the use of borates as preservatives had minimal impact when compared to the natural occurrence of borates (Li 2005).

The treatment process of borates is similar to that of CCA, however, borates unlike most other preservatives remain water soluble and mobile within the wood if there is enough moisture. While mobile the borate can diffuse throughout the cross section of the lumber providing deeper penetration of the preservative than most wood preservatives. Once dry the borate remains stable. However, once the wood becomes wet borate will again become mobile. During extreme wetting events the borate can diffuse out of the lumber leaving the lumber unprotected.

The treatment for solid wood is a water-soluble disodium octaborate tetrahydrate (DSOT) which is applied through pressure treatment similar to CCA. The concentrations are approximately 0.9% of DSOT to prevent fungi growth and approximately 1.5% of DSOT to prevent termites (Li 2005). OSB is treated during the manufacturing process. Zinc Borate is used and added during the flake mixing stage. The concentration of zinc borate to prevent fungal growth and termites is approximately 0.75% (Li 2005).

The methods by which borate acts as a preservative are not clearly understood. As an insect preservative it is believed that borate disrupts the digestive process of insects causing them to starve to death. As a fungal preservative it is believed that borate prevents enzymic activity at the cellular level. Borate is able to achieve this at relatively low levels of concentrations within the wood product. (Li 2005)

2.4.1.4 Discussion of Preservatives

Preservatives in lumber have been used for over a century in order to prevent damage or infection from insects and fungi. However, as previously stated because of health concerns with some preservatives the public and regularly boards have required the industry to develop and use preservatives with low toxicity in order to prevent ecological damage and well as have minimal impact on human health. Therefore, preservatives such CCA are being slowly phased out and preservatives such a borate with low toxicity are being employed.

3 Past Research

Within this chapter past research in the area of mould growth and mould growth prevention will be examined. Most mould studies have been conducted on natural food sources and agar mixtures in carefully controlled conditions. Four different studies were found that are the most appropriate and closely related to this study.

3.1 H. A. Viitanen (Mould Growth on Wood)

Viitanen pioneered research in the area of quantifying and predicting mould growth on wooden materials. Viitanen quantified mould growth using a visual scale and predicted mould growth on wooden materials using a mathematical model, both of which he developed using small samples in the lab. (Viitanen 1999)

The scale Viitanen developed quantifies mould growth based on visual observations, Table 3-1. Note that the scale is not limited to integer values.

Table 3-1: Mould Growth Scale (Viitanen 1999)

0	no growth
1	some growth detected only with microscopy
2	moderate growth detected with microscopy (coverage more than 10%)
3	some growth detected visually
4	Visually detected coverage more than 10%
5	Visually detected coverage more than 50%
6	Visually detected coverage 100%

Viitanen's mould growth model is a set of empirical formulas specially developed to predict mould growth on wooden materials. The model determines the minimum relativity humidity for mould growth to start (Equation 1, valid for temperature between 5 and 40 degrees Celsius), the largest possible extent of mould growth (Equation 2), growth rate in steady state conditions (Equation 3), and growth rate in varying conditions (Equation 8) all as a function of relative humidity and temperature. The validity of the mathematical model was calibrated though experimentation on small samples measuring 7 x 15 x 50 mm. The mathematical model is outlined below.

$$RH_{crit} = \begin{cases} -0.00267T^3 + 0.160T^2 - 3.13T + 100.0 & when \quad T \le 20 \\ 80\% & when \quad T > 20 \end{cases}$$ Equation 1

$$M_{\max} = 1 + 7\frac{RH_{crit} - RH}{RH_{crit} - 100} - 2\left(\frac{RH_{crit} - RH}{RH_{crit} - 100}\right)^2$$ Equation 2

$$\frac{dM}{dt} = \frac{1}{7\exp(-0.68\ln T - 13.9\ln RH + 0.14W - 0.33SQ + 66.02)}k_1 k_2$$ Equation 3

$$t_m = \exp\left(-0.68\ln T - 13.9\ln RH + 0.14W - 0.33SQ + 66.02\right)$$ Equation 4

$$t_v = \exp\left(-0.74\ln T - 12.72\ln RH + 0.06W + 61.50\right)$$ Equation 5

$$k_1 = \begin{cases} 1 & when \quad M < 1 \\ \dfrac{2}{t_v / t_m - 1} & when \quad M > 1 \end{cases}$$ Equation 6

$$k_2 = 1 - \exp\left[2.3\left(M - M_{\max}\right)\right]$$ Equation 7

$$\frac{dM}{dt} = \begin{cases} -0.032 & when \quad t - t_1 \le 6h \\ 0 & when \quad 6h \le 6t - t_1 \le 24h \\ -0.016 & when \quad t - t_1 > 24h \end{cases}$$ Equation 8

RH_{crit}	[%]	Minimum Relativity Humidity to Initiate Mould Growth (%)
T	[ºC]	Temperature of Surface
RH	[%]	RH at Surface
$\frac{dM}{dt}$	[-]	Time-Dependant Mould Index
W	[-]	Species of Wood (0 = Pinewood, 1 = Whitewood)
SQ	[-]	Surface Quality (0 = sawn after drying,1 = chamber dried)
k_1	[-]	Correction Factor

k_2	[-]	Correction Factor
t_m	[weeks]	Duration Until Mould Index 1 is Reached
t_v	[weeks]	Duration from Mould Index 1 to Mould Index 3
t	[d]	Time
M	[-]	Mould Index

When determining the growth rate for conditions which are varying a combination of Equation 3 and Equation 8 is required.

Viitanen observed no mould growth at a relative humidity equal to or lower than 75%. He also found:

1. The lowest relative humidity conditions which allowed for mould growth were at 80 to 85% RH.
2. Temperature conditions had little affect on the rate of mould growth.
3. Varying relative humidity conditions retarded the latent period (time to germinate) and growth rate below that of constant conditions.

The mould growth index versus time for different constant relative humilities at 26°C is plotted in Figure 3-1. It can be seen that relative humidity has a strong impact on the rate of mould growth as well as the maximum extent of mould growth.

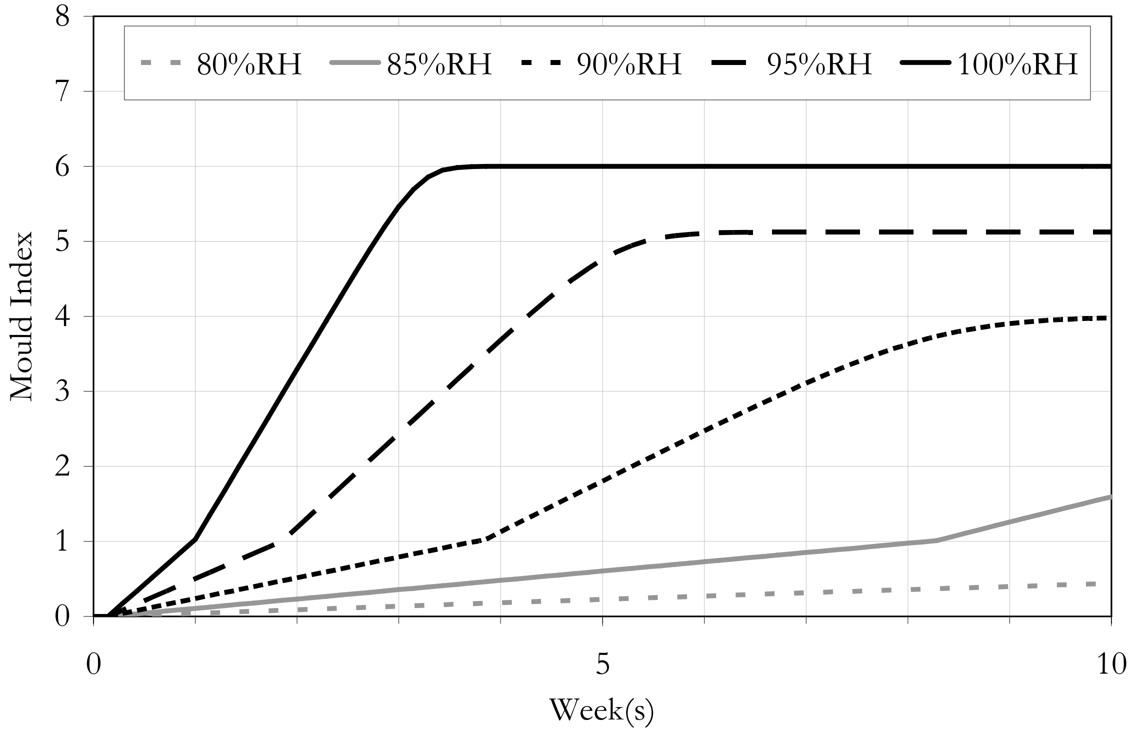

Figure 3-1: Predicted Mould Growth Rate at 26ºC Using Viitanen's Mould Growth Model

3.2 Klaus Sedlbauer (Influence of Substrate)

Sedlbauer, a researcher at the Fraunhofer Institute for Building Science, also developed a mathematical model to predict the formation of mould growth. He validated this model through laboratory testing. The mathematical model Sedlbauer developed is used by WUFIBIO a software package, to predict mould growth, which will be described in later chapters. Some of Sedlbauer's other research will be examined in further detail here

Sedlbauer's research concluded that all three conditions (temperature, substrate and relative humidity) must be present simultaneously over a period of time for mould growth to occur. The most relevant research to this study which Sedlbauer worked on was his research on the affect the substrate had on mould growth. Sedlbauer categorized substrates into four different categorizes (0, I, II, III). Substrate 0 being the optimal substrate and Substrate III being one which does not support mould growth as it does not degrade or contain nutrients.

Substrate I materials utilize reconditioned biological material, such as paper faced drywall, biological degradable building materials, and materials with permanently elastic joints such as caulking. Substrate II materials are porous such as plasters, mineral based building materials, certain types of wood, and insulating materials not covered under the Substrate I categorization. Using these substrate categorizations, Figure 3-2 was developed which indicates how the substrate impacts the formation of mould.

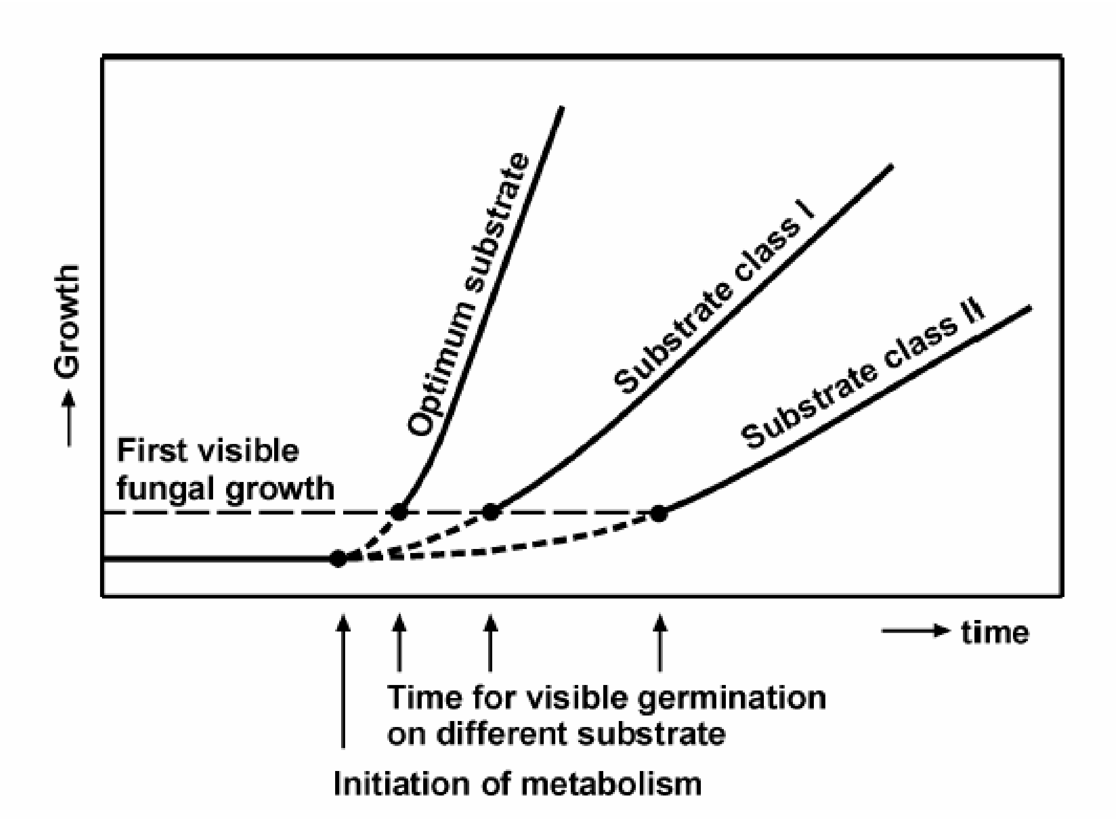

Figure 3-2: Influence of Substrate on Mould Growth (Sedlbauer 2001)

3.3 Susan Doll (Mould Growth on Different Building Products)

Doll determined the growth rate of mould on different building materials. Doll's thesis "Determination of Limit Conditions for Fungal Growth in the Built Environment" was broken into a number of major sections (Doll 2002). The two sections of most interest are one entitled "Fungal Growth on Uninoculated Gypsum Wallboard" and another entitled "Latent Period and Fungal Growth on Four Common Building Materials".

Within the first major section she determined the affect of sterilization has on uninoculated gypsum wallboard at different moisture conditions, 95% RH, 10% of Saturation, 20% of Saturation. Doll concluded from her test that before performing a study with known fungal species it is necessary to sterilize the test samples before inoculation. More importantly, Doll found there was enough fungal contamination introduced from the manufacturing process that inoculation of samples was not necessary if the researcher was not interested in studying specific known fungal species. Doll also found that unless samples were exposed to wetted conditions, mould growth was minimal after 5 weeks.

The second section of her thesis examined the latent period and fungal growth on samples using naturally occurring fungal infections rather than inoculation. Samples were exposed to varying RH and partially saturated conditions. Tested samples included gypsum wallboard, ceiling tiles, plywood, and OSB. There was no growth on the samples exposed to a relative humidity of either 75% or 85% during the 8 week test. Growth was very slow and only covered 5% of the sample after 8 weeks at relative humidity of 95%. Samples exposed to a relative humidity of 100% were completely colonized in three weeks, and samples which were partially saturated were completely covered in two weeks. It was observed that at a relative humidity of 100% or above there was no difference between the behaviour of the four materials. The growth rate increased and the latent period decreased as moisture content increased.

Even though many have indicated that a relative humidity of between 70-90% is a minimum relative humidity required for fungal growth to occur (Doll 2002), Doll's thesis clearly showed that wetting conditions are necessary to have significant mould growth in time periods of less than about 2 months.

3.4 Raymond Li (Affect of Borate Treatment)

Another very closely related study was a Masters thesis by Raymond Li entitled "Mould Growth on Building Materials and the Effects of Borate-Based Preservatives" (Li 2006). In his research Li examined three different types of moulds which have been associated with health problems, and determined how effective borate-treatment was against these on six different building materials: Southern Yellow pine, Lodgepole Pine, Pine Oriented

Strandboard, Aspen Oriented Strandboard, Cellulose Insulation, and Gypsum Wall Board. Small samples were placed in incubation chambers kept at room temperature (20 to 23ºC) for 29 days. The mould growth rate was determined through weekly visual inspections and weekly volatile organic compound testing. Similar to work done by Doll, testing of the materials were done on a small scale with material samples being cut into 7 cm squares except for the cellulose insulation which used samples weighing 2 to 3 grams.

Li concluded that borate-based preservatives are effective as they were able to reduce the mould growth on all the materials tested. However, it was found that the OSB samples may require higher levels of treatment than are currently employed in the industry.

3.5 Discussion of Past Research

The past research examined within this section provided the basis for the experimental setup and operation, and further provide adequate information for later discussion. Both Viitanen and Doll indicated that no mould growth should be expected for conditions lower than 85% within a reasonable amount of time. Results from Sedlbauer's research demonstrated the influence of substrate quality on mould growth. His results showed that one can expect varying lengths of time to observe mould growth and varying rates of the mould growth for different materials. Li showed that borate based preservatives can lengthen the latent period and reduce the rate of mould growth. Past research was done on small samples which do not include variations that occur in full-scale construction, such as changing material characteristics over the face of the sample, micro-variations in temperature and relative humidity at three-dimensional construction details, and gradients of both temperature and moisture. The amount of research on common building materials is limited and more data and more replications and more temperature, humidity, and material types are needed.

4 Moisture Physics and Material Properties

As previously mentioned the accepted method of practical mould control in most cases is to remove the source of water. Moisture control is a balance between wetting, drying, and safe storage capacity. Damage occurs when the safe storage capacity of a material is exceeded. Figure 4-1 illustrates this moisture balance between wetting, drying and safe storage capacity.

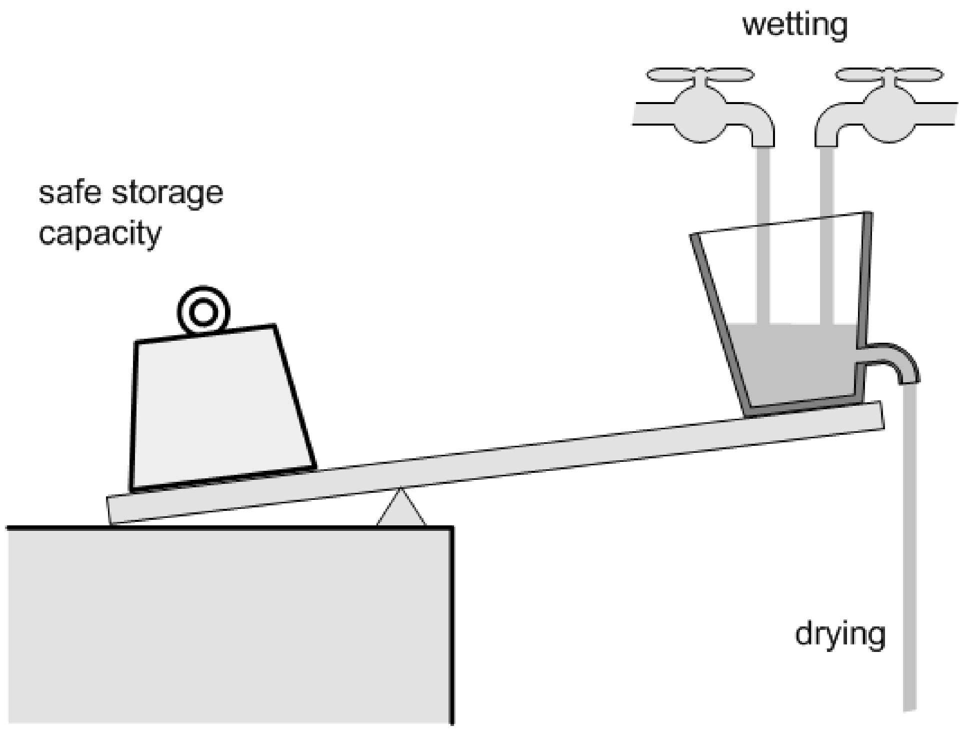

Figure 4-1: Moisture Balance (Straube 2005)

Figure 4-2 illustrates most common wetting and drying processes along with the mechanisms which transport the moisture in and out of the enclosure.

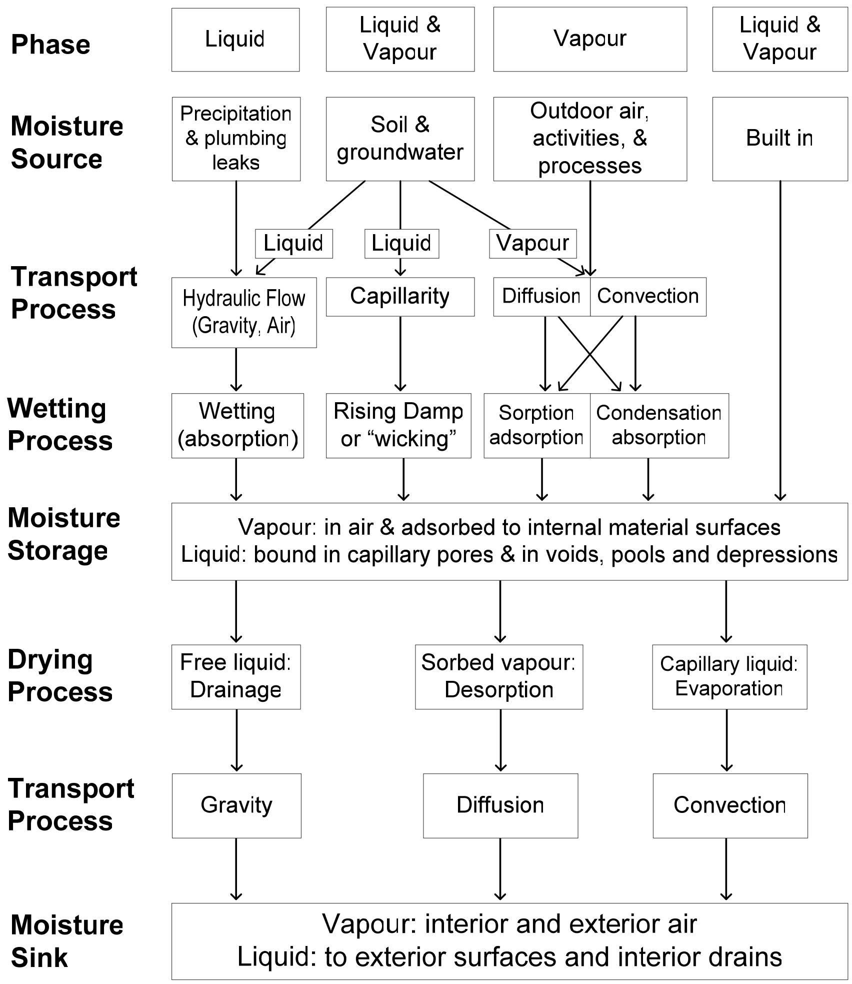

Figure 4-2: Wetting, Drying, and Storage Processes in a Building Enclosure (Straube 2005)

Within this section the wetting and drying processes which pertain to this study will be examined.

4.1 Psychrometrics

Psychrometrics is the term used to define the relationship of air and its energy and water vapour content.

Water in its gaseous state is referred to as water vapour, and at any given temperature there is a maximum amount of water vapour the air can hold. The moisture content of air can be measured gravimetrically (in units of kg of H_2O per kg of air) or by the partial pressure exerted by the water vapour (in units of Pascals). When the maximum amount of water vapour the air can hold is reached, it is termed saturated. An approximation of the saturation vapour pressure at any given temperature can be calculated using Equation 9.

$$P_{ws} = 1000 \cdot \exp(52.58 - \frac{6790.5}{T} - 5.028 \ln T) \quad \text{Equation 9}$$

P_{ws}	[Pa]	Saturation Water Vapour Pressure
T	[K]	Temperature (Over 0 Celsius)

Relative humidity is the ratio of the actual amount of water vapour in the air to the maximum allowable amount of water vapour in the air (saturation vapour pressure). This ratio is defined by Equation 10.

$$RH = \frac{P_w}{P_{ws}} \quad \text{Equation 10}$$

P_{ws}	[Pa]	Saturation Water Vapour Pressure
P_w	[Pa]	Water Vapour Pressure

Figure 4-3 is a plot of a psychrometric chart. Such charts are a common tool used both within the building science profession as well as in the heating, ventilating and air conditioning industry. Plotted on this chart is the saturated vapour pressure of the air versus the air temperature and the relative humidity.

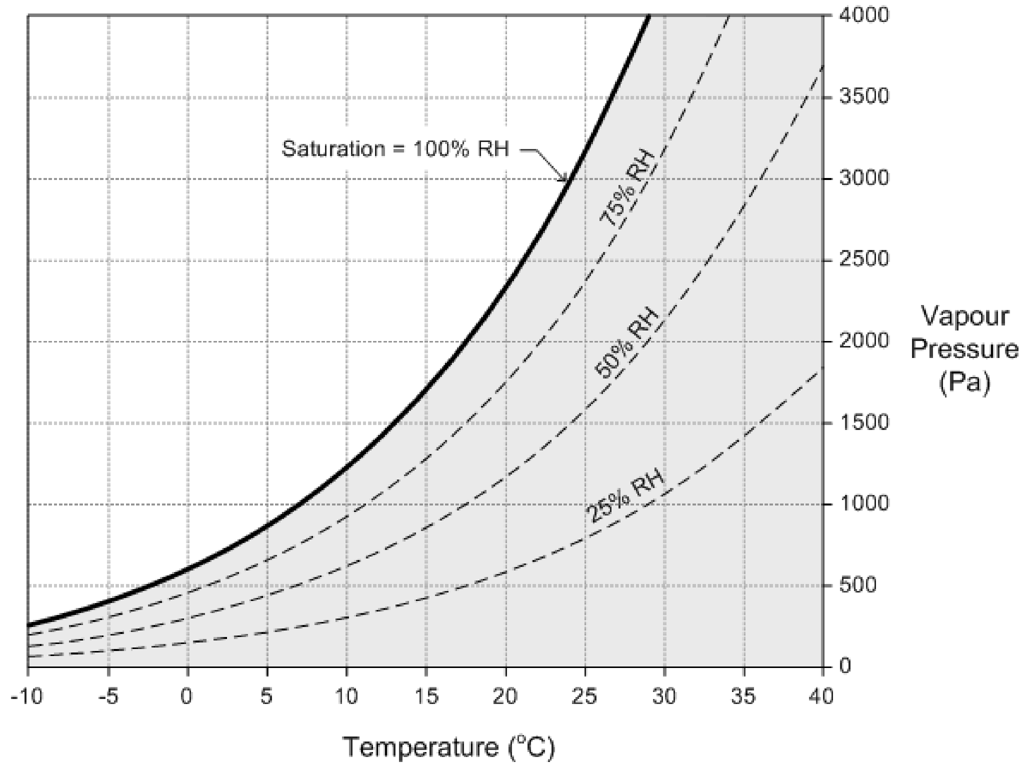

Figure 4-3: Psychrometric Chart

For an example in the use of the psychrometric chart refer to Figure 4-4. Point A on Figure 4-4 represents a sample of air with a temperature of 35ºC and a relative humidity of 60%. If this sample of air is cooled to 20ºC, the condition of the air moves horizontally at a constant vapour pressure towards Point C on the chart, eventually reaching Point B where it intersects the saturation vapour pressure line. At this point condensation will start to occur, and as one lowers the air temperature further condensation will continue until the desired temperature of 20ºC is reached.

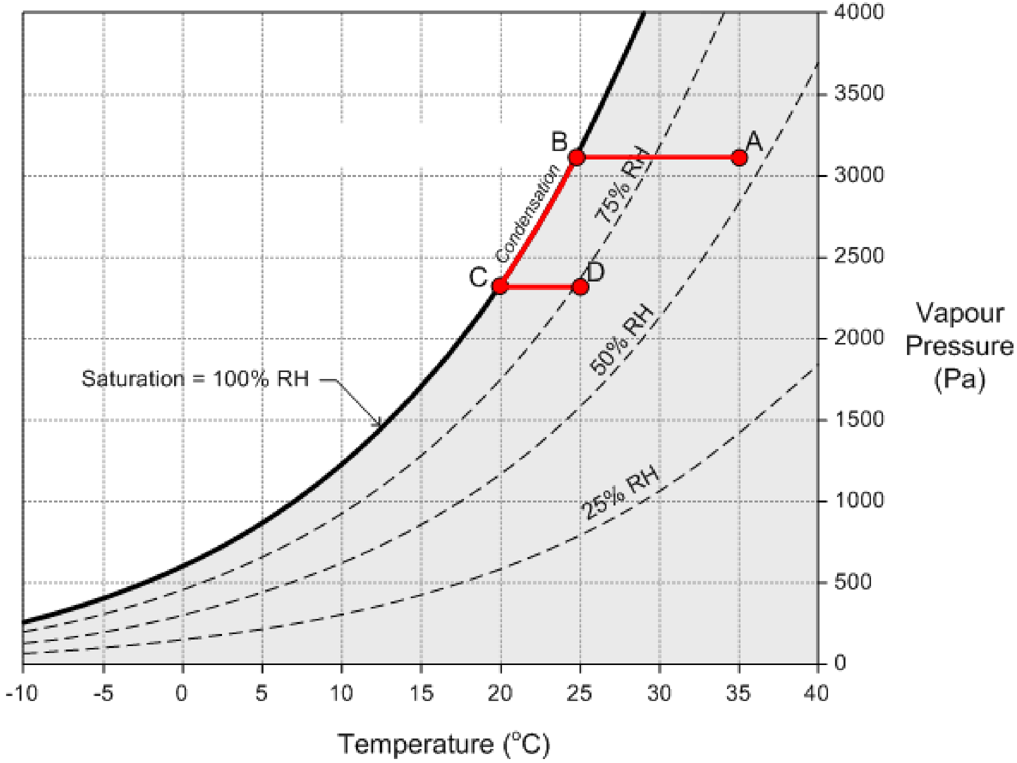

Figure 4-4: Condensation Example

The point at which the condensation will start to occur for any sample of air is called the dewpoint temperature. This temperature is mathematically represented by Equation 11.

$$t_d = \frac{4030}{18.689 - \ln\left(\frac{P_w}{133}\right)} - 235 \qquad \text{Equation 11}$$

P_w	[Pa]	Water Vapour Pressure
t_d	[°C]	Dewpoint Temperature

If the sample of air in the example were heated from Point C to Point D, the air would change its condition to a temperature of 25°C and a relative humidity of 75% by moving horizontally along a constant vapour pressure.

4.2 Convection and Diffusion

Water vapour utilizes two primary modes of transport: convection and diffusion.

Convection is the movement of mass or energy by movement of a fluid, either a liquid or gas. For building scientists, convection is the transport of water vapour through the movement air by the building enclosure. Air leakage is used to describe the process of air movement through unintended locations within the building enclosure. For this study because great care has been taken to ensure no air leakage occurs through the test wall, it will be assumed that convection is not a mode in which water vapour will be transported through the wall.

Diffusion is the transfer of mass or energy from a higher concentration to a lower concentration. Diffusion was the primary mode of water vapour transport utilized in the experiments described later.

Fick's Law (Equation 12) is used in steady state diffusion calculations.

$$\frac{dm}{d\theta} = -D \cdot \nabla C \qquad \text{Equation 12}$$

$\frac{dm}{d\theta}$	[-]	Mass Flow per Unit of Time
∇	[-]	Divergent Operator
D	[-]	Diffusivity of Medium
C	[-]	Concentration of Species That is Diffusing

Equation 12 can be presented in the form of Equation 13. Equation 13 is the practical form that can be used to calculate the amount of water vapour that is transported through a wall assembly due to diffusion.

$$q_v = \frac{1}{R_v} \cdot \Delta P \qquad \text{Equation 13}$$

q_v	[ng/s]	Rate of Flow
R_v	$[Pa \cdot s \cdot m^2 / ng]$	Vapour Resistance
ΔP	[Pa]	Vapour Pressure

4.3 Hygrothermal Properties of Oriented Strandboard and Plywood

Wood is a hygroscopic material, continually exchanging water vapour with the environment it is located within. When wood is relocated from an environment of low relative humidity to high relative humidity it adsorbs water vapour and when it is moved from an environment of high relative humidity to one of low relative humidity it releases water vapour. Therefore, the moisture content of the wood is related to the relative humidity of the environment surrounding it. A sorption isotherm is a graphical representation of this relationship between the moisture content of a material and the surrounding relative humidity at a particular temperature. Figure 4-5 is a typical sorption isotherm of a hygrothermal porous material such as wood. The sorption (uptake) of water vapour is represented by the bottom line and desorption (release) of water vapour is represented by the upper line.

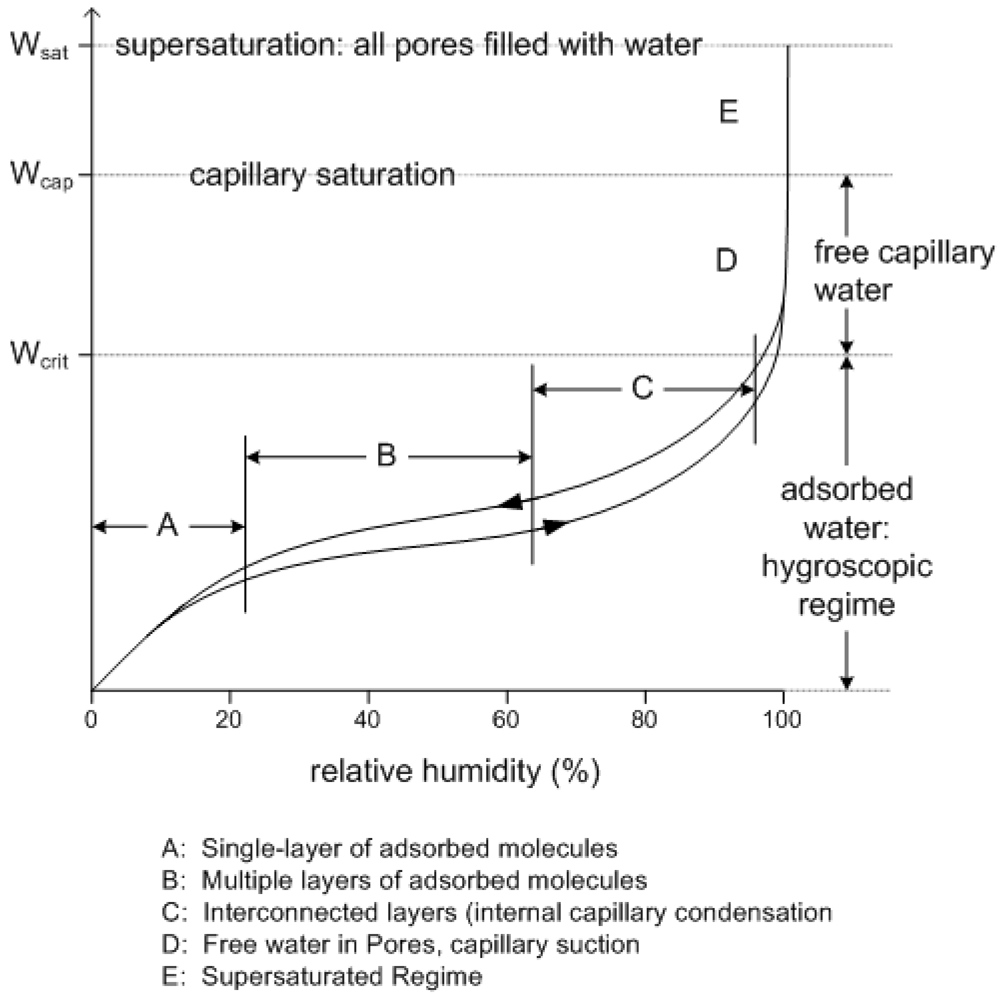

Figure 4-5: Typical Isotherm of a Hygrothermal Porous Material (Straube 2005)

The Institute for Research in Construction (IRC) performed materials testing on many building materials, including OSB and plywood. Using the published data from these reports it was possible to construct a sorption isotherm illustrate by Figure 4-6.

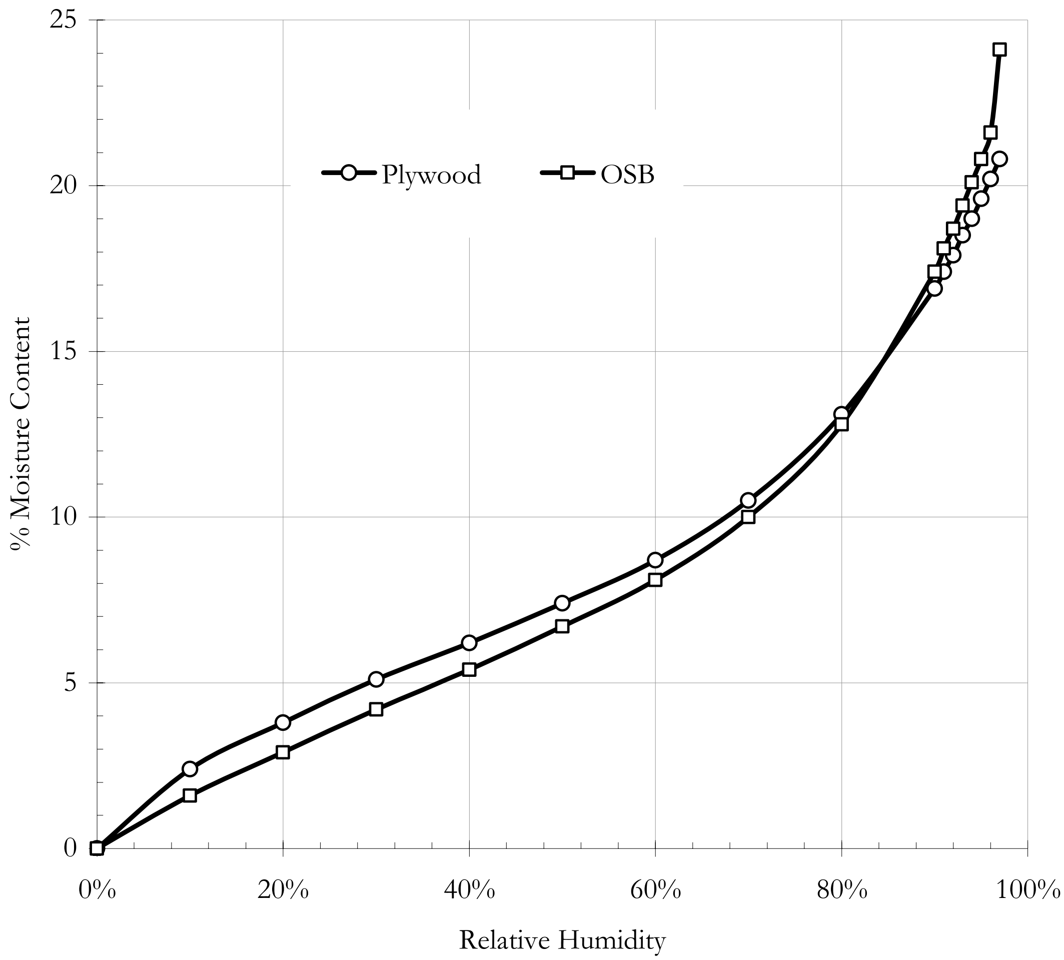

Figure 4-6: Sorption Isotherm for OSB and Plywood (Kumaran et al 2002)

The vapour permeability of wood is very closely related to its moisture content which in turn is related to the relative humidity of the surrounding environment. In addition to calculating the moisture content as a function of relative humidity the IRC also calculated the permeance of 11.1 mm OSB and 12.7 mm Plywood as a function of relative humidity. Figure 4-7 presents the results of this test. It can be seen that the permeance of both hygroscopic materials changes dramatically with the relative humidity. There is a greater effect on the permeance of plywood as compared to the OSB for the same changes in relative humidity. At a relative humidity of 90% plywood is 3 times more vapour permeable than OSB.

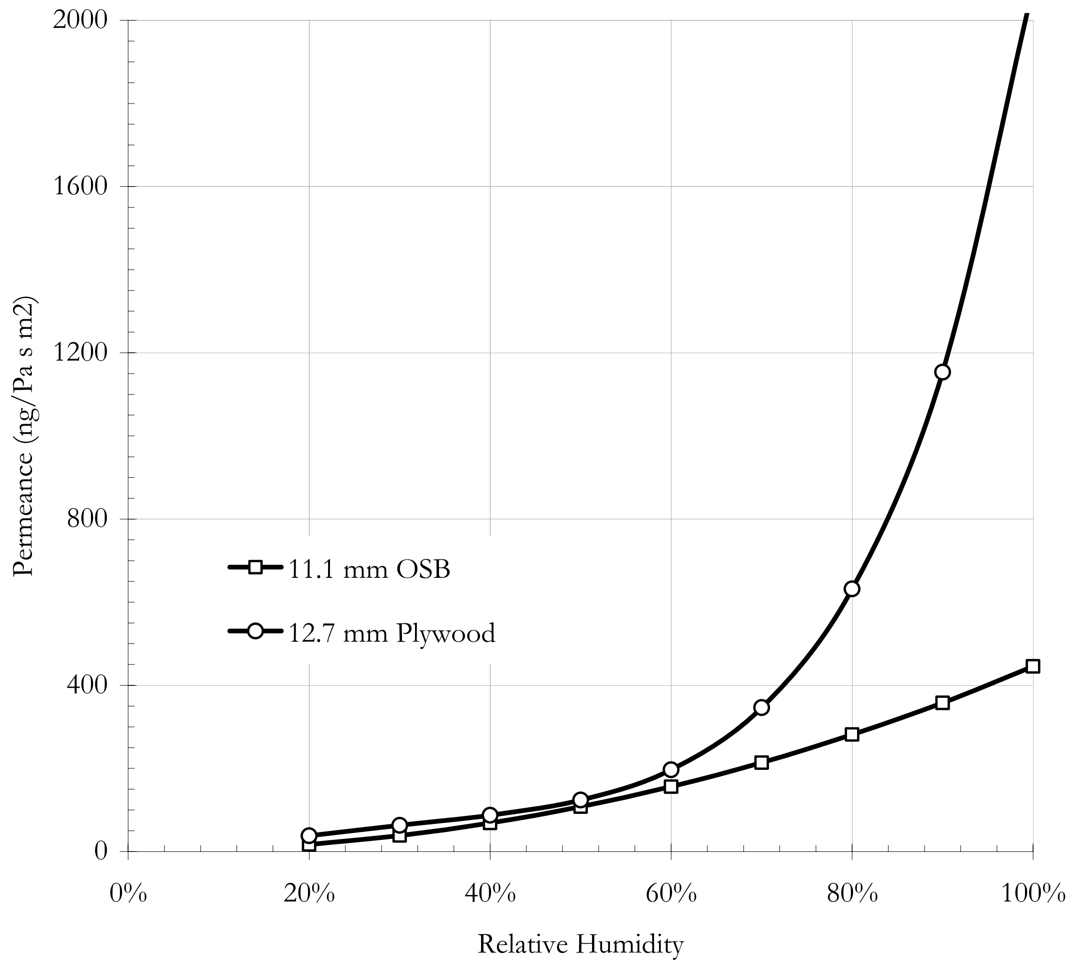

Figure 4-7: Vapour Permeability versus Relative Humidity of OSB and Plywood (Kumaran et al 2002)

5 Experimental Plan and Test Variables

5.1 Experimental Objective

The objective of the experimental work was to determine the mould resistance of different types of wood products including different types of wood treatments. Additional objectives included comparing the results of the experiment to mould growth models.

5.2 Experimental Scope

The scope of the experiment was limited to a select number of wood products and only one type of treatment. A unique feature of this experiment was the use of full scale wall assemblies with gradients of relative humidity and temperature. This is very different than previous studies which performed small scale material testing within a laboratory under very stable conditions. A commissioning and three test series were completed. The commissioning test was only used to demonstrate and commission the operation of the chamber. The experimental results are compared to two different types of mould growth models.

5.3 Experimental Approach

The first step was to construct a climate chamber which would be able to accurately and reliably produce relative humidity and temperature conditions required to grow mould. Following the construction of the climate chamber, several full scale test wall assemblies were constructed out of the provided test materials. The test wall assemblies were instrumented to measure the conditions being imposed by the climate chamber and to aid in the understanding of mould growth. During each test the mould growth on each wall assembly was visually inspected to quantify the extent of mould growth. Several different wall assemblies were tested under different steady state and varying conditions in order to meet the experimental objectives. Finally the results of the experiments were compared to the Viitanen's mould growth model and the WUFIBIO mould growth model.

5.4 Test Variables

Within this study three types of dimensional lumber and two types of sheathing were tested. As previously stated the emphasis of this study was on the sheathing and not the dimensional lumber. The types of dimensional lumber tested were Southern Yellow Pine, Spruce Pine Fir, and Douglas-Fir and the types of sheathing being tested are Oriented Strand Board and Plywood. All five types of wood products were tested either as untreated or Borate treated.

5.5 Boundary Conditions

In order to meet the objectives of this study four tests were performed. The first of which was a commissioning test which was used to demonstrate and commission the operation of the climate chamber. The remaining three tests were used to meet the objectives of the study. The objectives for the conditions are expressed by the target surface relative humidity for interstitial facing side of the sheathing. The three tests boundary conditions arranged in chronological order, were as follows:

Test Number 1:	Maintain a relative humidity of 95% (Figure 5-1).
Test Number 2:	Prolonged condensation conditions (Figure 5-2) until the moisture content starts to stabilize at which point the conditions are lowered to maintain a relative humidity of 95% (Figure 5-4).
Test Number 3:	Fluctuating condensation conditions: 8 hours of condensation conditions (Figure 5-3), followed by 16 hours at a relative humidity of 80% (Figure 5-4).

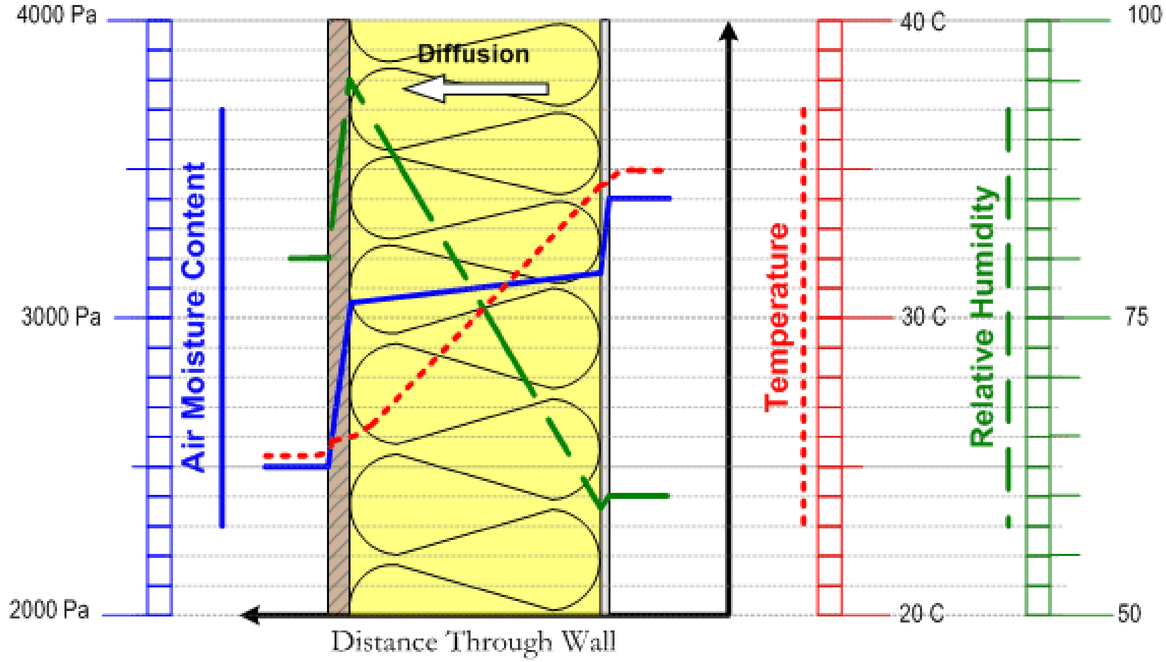

Figure 5-1: 26°C and 95% Relative Humidity at Back of Sheathing

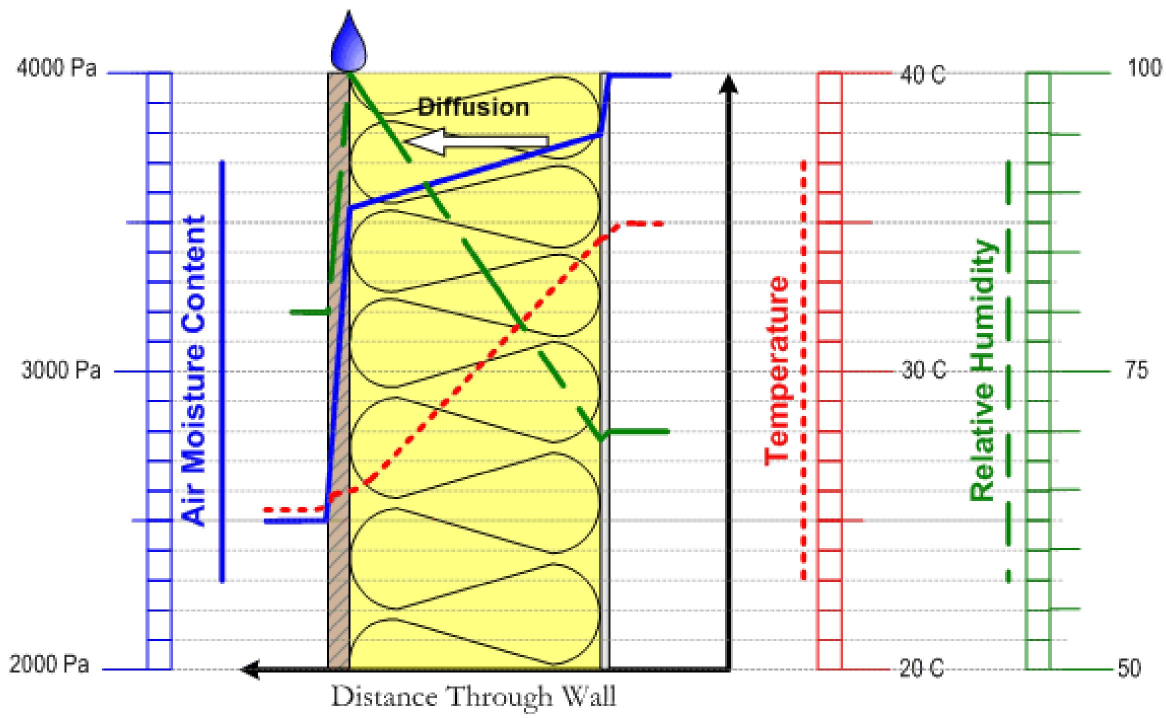

Figure 5-2: 26°C and Condensation Conditions at Back of Sheathing

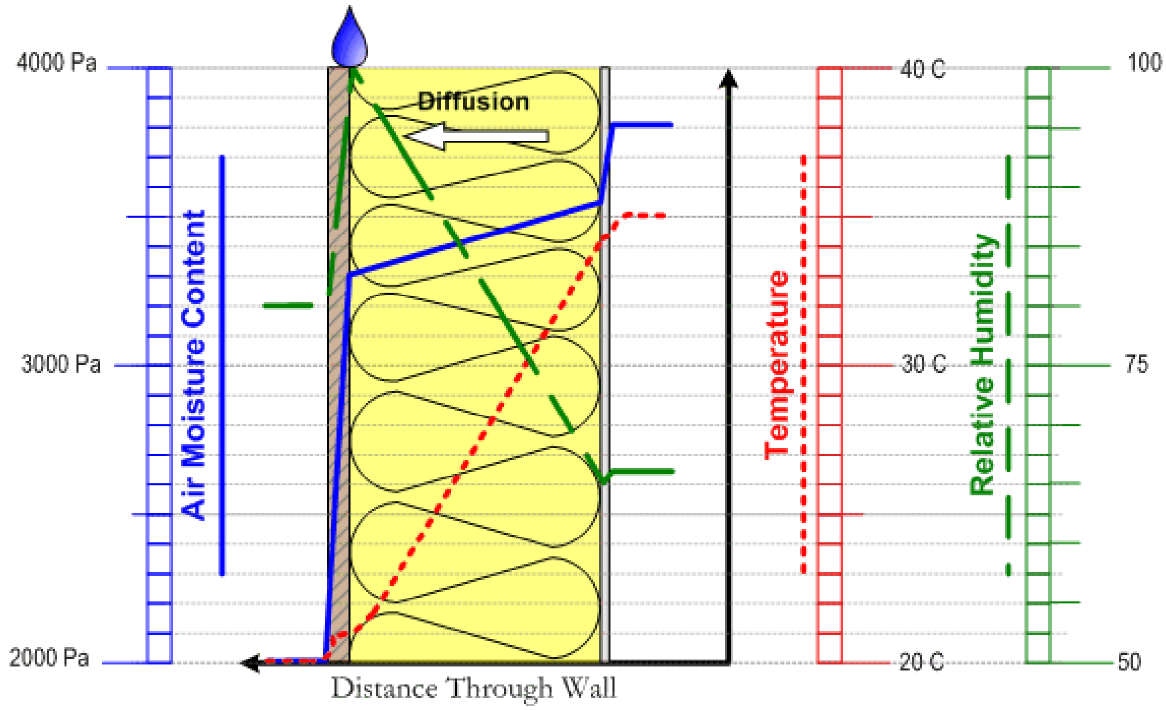

Figure 5-3: 20°C and Condensation Conditions at Back of Sheathing

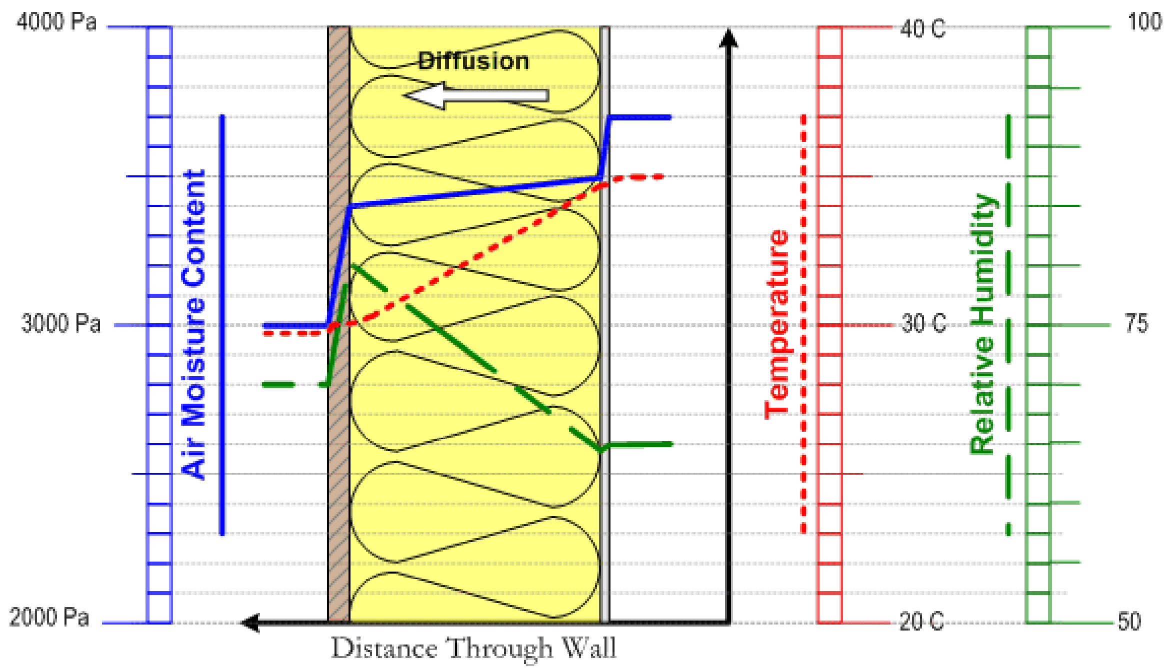

Figure 5-4: 30°C and 80%Relative Humidity at Back of Sheathing

6 Experimental Setup and Apparatus

6.1 Climate Chamber

Previous studies have shown conditions of high relative humidity (over 85%) and relatively high temperatures (over 5ºC) are required to encourage mould growth. Therefore, in order to impose these conditions on the sheathing of an insulated full-scale wood frame wall assembly, a gradient of temperature and humidity was imposed. To impose this gradient the Building Engineering Group's steady-state climate chamber was used. The chamber was configured to allow the side-by-side comparison of two full scale test assemblies. Shown in Figure 6-1 is a photograph of the chamber. Figure 6-2 illustrates the layout of the chamber, and construction drawings can be found within Appendix A.

Figure 6-1: Steady-State Climate Chamber

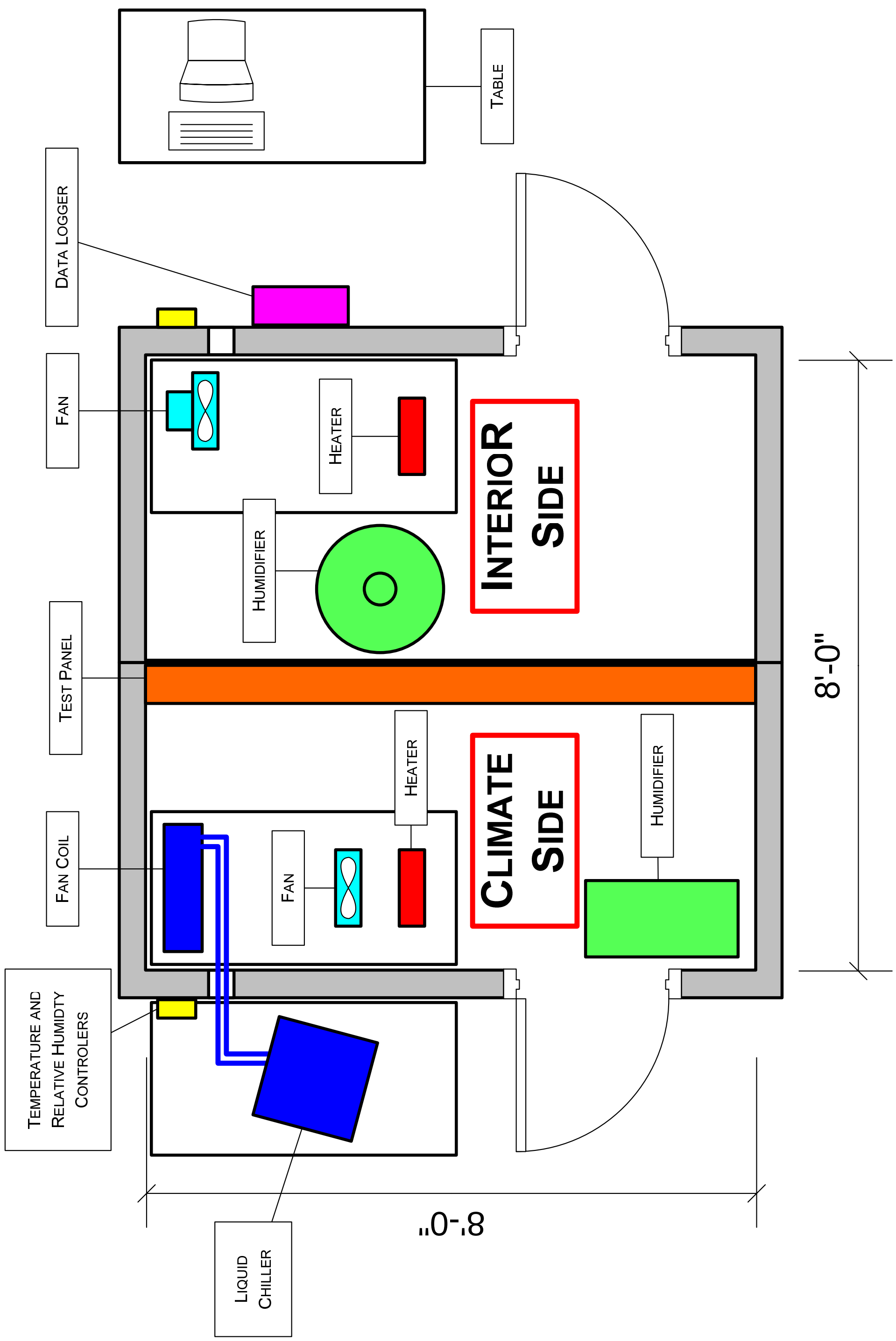

Figure 6-2: Plan of the Steady-State Climate Chamber

6.1.1 Climate Chamber Design

The structure of the climate chamber is framed using 2" x 4" dimensional lumber for the walls and 2" x 6" dimensional lumber for the floor. The exterior of the chamber is covered with sheets of plywood which adds additional rigidity to the structure. The climate chamber can be split and moved if necessary.

All eight sides of the climate chamber were insulated with 4" of fibreglass batt insulation and then two pieces of 1" aluminium faced polyiso expect for the floor which was insulated with 6" of Batt insulation and again two pieces of 1" polyiso. The entire inside of the chamber was covered with white tile board which has a low permeance material. The only remaining joints in the interior of the climate chamber were subsequently filled with silicon. The large amount of insulation and extra care to insure air leakage was minimized allowed the chamber to respond quickly to experimental climate demands while requiring minimal heating, air conditioning, and humidification equipment.

Additional features were incorporated into the design of the climate chamber to make it a more versatile piece of test equipment. In insert a test wall assembly within the climate chamber, the climate chamber was able to separate into two halves. The test assembly was then placed in the climate side of the chamber and secured in place. The two halves of the climate chamber were then brought back together using a winch. The winch ensured the gaskets which separated the climate chamber were tightly sealed and that air leakage between them was minimized. The climate chamber was raised off the floor to allow easier separation of the halves. This was accomplished by adding nine 2" x 6" pieces of lumber on the bottom of the chamber. This feature allowed for a fork lift or trolley truck to easily lift and separate the climate chamber, and when required bring the climate chamber back together close enough for the winches located on the side of the climate chamber to complete the process of sealing. The final feature added to the climate chamber was the ability to disassemble the chamber into sixteen pieces which allowed the chamber to be easily transported within the school or to other facilities.

6.1.2 Control System

To control the conditions within each side of the chamber a liquid chiller system with a fan coil unit, a pair of humidifiers, and a pair of heaters was used, and during the last test a 150W light bulb was used as an additional heat source. As per Figure 6-3, on the climate side of the climate chamber the fan coil unit was used to remove water vapour from the air (dehumidifier) by forcing air (Point A) to pass through the fan coils which were maintained at a desired dewpoint (Point C), and then the heater was used to heat the air up again to the desired temperature (Point D). The humidifier on the climate side of the climate chamber was used to quickly return conditions in the climate chamber after the door was opened. The interior side of the climate chamber was designed to operate at higher conditions than that of the climate side and therefore no dehumidification equipment was required. The humidifier raised the relative humidity of the interior side of the climate chamber to the desired conditions. The heater raised the temperature to the desired temperature. The fans on both sides of the climate chamber maintained an even distribution of conditions through each side of the climate chamber. This equipment was controlled through two Dwyer programmable relative humidity and temperature relays which were located on either side of chamber. A combination of this equipment along with the extremely airtight and vapour impermeable climate chamber allowed for mould growth conditions to be easily reached and maintained.

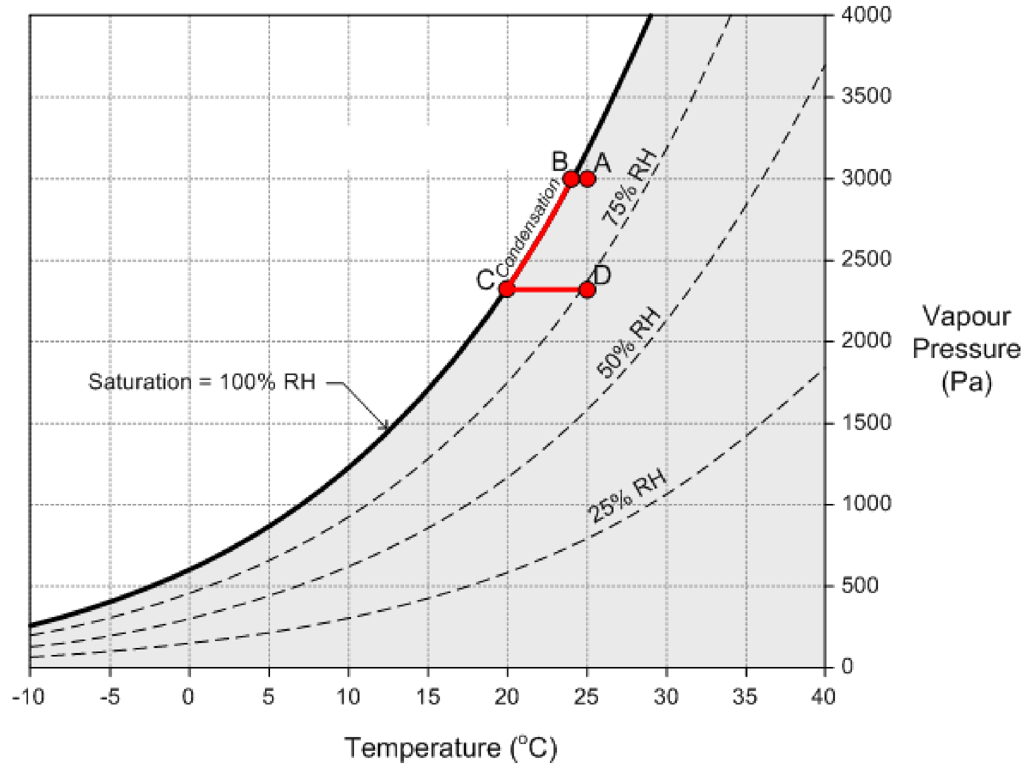

Figure 6-3: Fan Coil Operational Example

6.2 Test Wall Panel Design

The test wall was designed and constructed to match standard construction practise as closely as possible while still being able to perform all the required tests. Unlike previous studies which were performed using small scale test samples this study performed tests on full scale wall assemblies which allow for more realistic testing allowing for variations between location and variations between the gradients within the test wall assemblies. Within each test wall assembly treated and untreated versions of the following products were used: OSB, Plywood, Douglas-Fir, Spruce Pine Fir, and Southern Yellow Pine. The wall assembly was framed using 2" x 4" lumber, insulated using R13 fibreglass batt insulations in the stud space. The sheathing was then placed on the exterior side of the wall assembly, and Tyvek™ was place on the interior side to air seal the wall assembly. Even though it is standard practice to install gypsum wall boards on the interior side of a wall assembly, Tyvek™ was used in lieu of the gypsum wall board because under the relative humidity conditions of the test the paper facing would have easily grown mould. Replacing the gypsum wall board with Tyvek™ did not affect the conditions experienced by the lumber within the wall assembly and the Tyvek™ did not support mould growth. As mentioned previously the care taken to avoid air leakage ensured the only method of water vapour transport through the test wall assembly was by diffusion.

The test panels were designed to allow for the maximum number of material test combinations while accommodating for redundancy within the wall design. The dimension of each test panel was 4' x 8' and these panels were divided into quadrants to maximize the combinations of different variables that can be tested, Table 6-1, Figure 6-4, and Figure 6-5. The sheathing used in each quarter was alternated between plywood and OSB. To prevent convective loops within each quarter, wood blocking was used as a separator. Each type of sheathing was located with an upper and lower quadrant to determine the influence location may have on the test outcome.

Table 6-1: Experimental Matrix for Sheathing

Quadrant	Product	Treated	Location
1	OSB	Yes	Upper
2	Plywood	Yes	Upper
3	Plywood	Yes	Lower
4	OSB	Yes	Lower
5	Plywood	No	Upper
6	OSB	No	Upper
7	OSB	No	Lower
8	Plywood	No	Lower

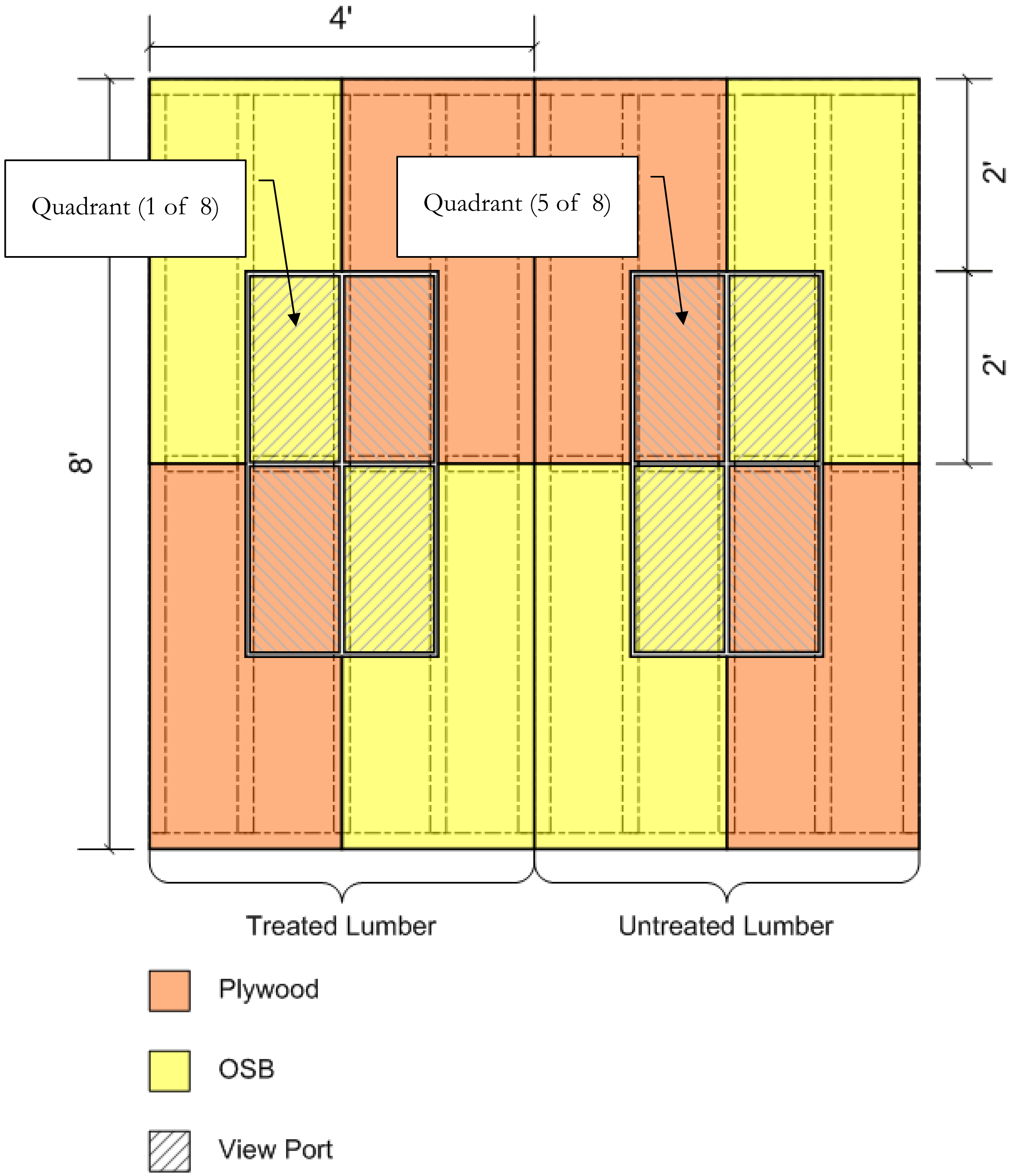

Figure 6-4: Sheathing Layout of Two 4' x 8' Test Panels

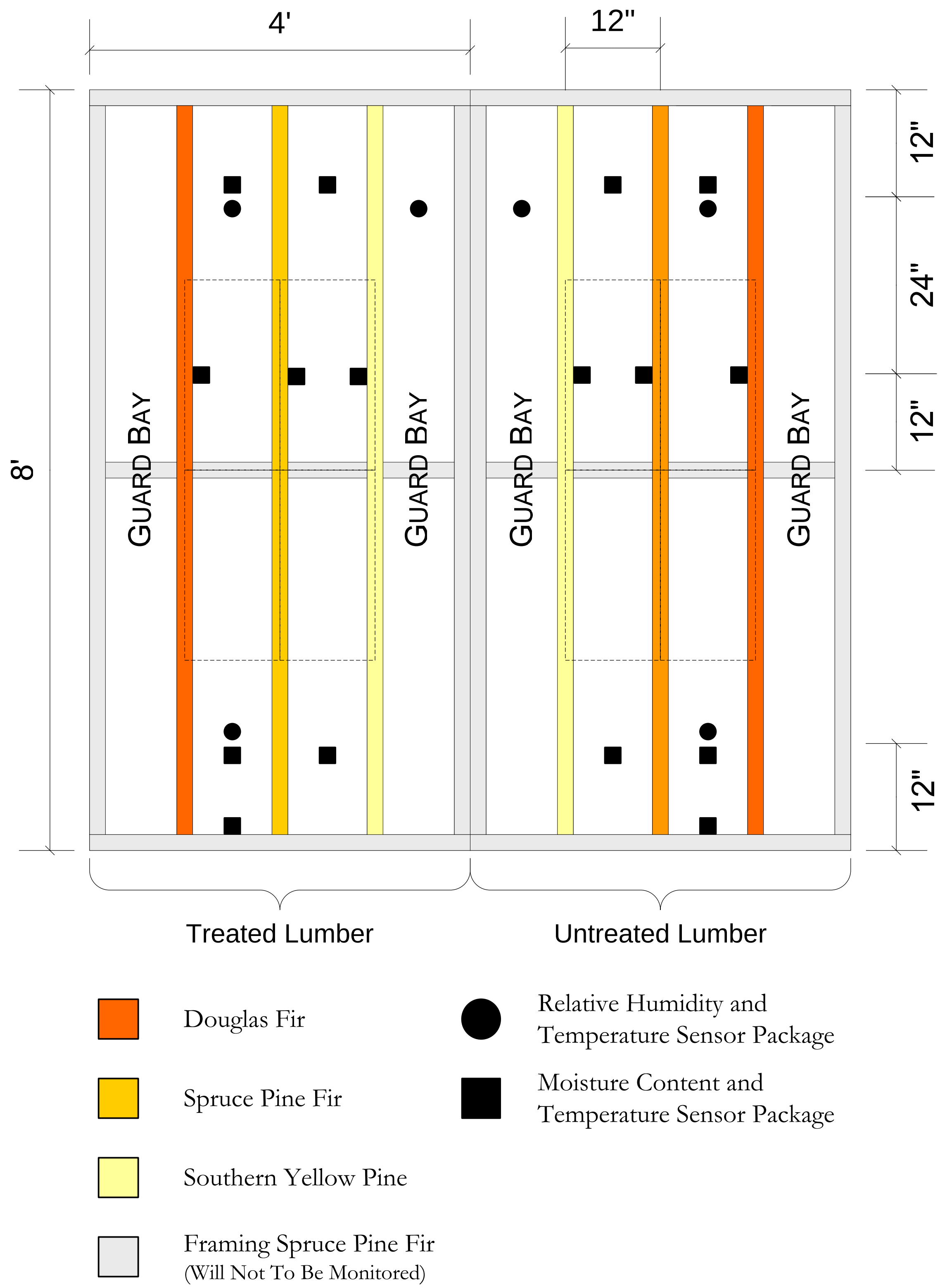

Figure 6-5: Test Panel Stud Framing Layout and Sensor Locations

Within each of the two test panels three types of sawn lumber were tested: Douglas-Fir, Spruce Pine-Fir and Southern Yellow Pine. Furthermore, each test panel was tested in a side by side comparison of untreated and treated samples. To avoid edge effects, no studs were tested on either side of the test panels (perimeter of climate chamber), which created a "guard bay". To accommodate the number of samples the studs were spaced at approximately 12" on center.

Each quadrant has a test port measuring 2' wide by 1' high which allows for its removal allowing for the examination of mould growth as well as inspection of all samples within the wall on a regular basis. A photo of each test port was taken on a regular basis. Located on the exterior of the climate chamber was a shelf used to mount the test ports in order to ensure repeatable photographs throughout the experiment. These steps ensured consistency between photographs allowing for better comparison between photographs.

As mentioned previously the permeability of both OSB and plywood increases as the relative humidity increases. However, the permeability of OSB and plywood increase at different rates and as a result it becomes difficult to run a side by side comparison of test wall assemblies with different sheathings while trying to maintain similar conditions. To compensate for this effect the walls were designed assuming the relative humidity behind the sheathing was 95%. Permeance values could have been chosen from Figure 4-7. However, a commissioning test was run to determine the approximate permeance of the wall system for the OSB and plywood used in this study. Based on the results of the commissioning test, and by comparing the results with known permeance values, a permeance of 650 $ng/Pa \cdot s \cdot m^2$ was chosen for the plywood and 300 $ng/Pa \cdot s \cdot m^2$ for the OSB. The assumed permeance values correspond to a relative humidity of 80% on the graph plotted in Figure 4-7, however, the values assumed for this study are based upon the actual test wall assemblies and not the data provided by the MEWS project used to generate this figure. Also, the relative humidity drops across the sheathing, from about 95% to about 80% RH.

Using these permeance values, a steady state vapour flow analysis was conducted for the conditions of the first test. Table 6-2 and Table 6-3 show the inputs and results for the plywood and OSB walls respectively. Although the relative humidity at the back of the sheathing is close to the target of 95% for the plywood wall, it is well over this target for the OSB wall. Hence, it was decided that instead of using one piece of Tyvek™ on the interior of the OSB test walls, three pieces would be used. The difference in construction of the walls and the impact on the relative humidity behind the sheathing can be seen in Table 6-4. Given this test setup, the relative humidity behind the OSB sheathing should be close to that of the plywood sheathing.

Table 6-2: Vapour Resistance of Plywood Wall Assembly

Layer	M_i (ng/(Pa*s*m^2))	Δ P_v (Pa)	Temperature (Celsius)	$P_{v,sat}$ (Pa)	P_v (Pa)	RH RH
			24.5	3074.1	2459.3	80.0%
Film	15000.00	22.0				
			24.8	3133.9	2481.3	79.2%
Plywood	650.00	508.1				
			25.1	3193.9	2989.4	93.6%
Batt	1633.33	202.2				
			34.7	5531.4	3191.6	57.7%
Tyvek™	2000.00	165.1				
			34.7	5531.4	3356.7	60.7%
Film	15000.00	22.0				
			35.0	5631.2	3378.7	60.0%

Table 6-3: Vapour Resistance of OSB Wall Assembly

Layer	M_i (ng/(Pa*s*m^2))	Δ Pv (Pa)	Temperature (Celsius)	$P_{v,sat}$ (Pa)	P_v (Pa)	RH RH
			24.5	3074.1	2459.3	80.0%
Film	15000.00	13.4				
			24.8	3133.9	2472.7	78.9%
OSB	300.00	669.3				
			25.1	3193.9	3142.0	98.4%
Batt	1633.33	122.9				
			34.7	5531.4	3264.9	59.0%
Tyvek™	2000.00	100.4				
			34.7	5531.4	3365.3	60.8%
Film	15000.00	13.4				
			35.0	5631.2	3378.7	60.0%

Table 6-4: Vapour Resistance of OSB Wall Assembly With Additional Tyvek™

Layer	M_i (ng/(Pa*s*m^2))	ΔP_v (Pa)	Temperature (Celsius)	$P_{v,sat}$ (Pa)	P_v (Pa)	RH RH
			24.5	3074.1	2459.3	80.0%
Film	15000.00	11.0				
			24.8	3133.9	2470.3	78.8%
OSB	300.00	549.4				
			25.1	3193.9	3019.7	94.5%
Batt	1633.33	100.9				
			34.7	5531.4	3120.6	56.4%
Tyvek™	667.00	247.1				
			34.7	5531.4	3367.7	60.9%
Film	15000.00	11.0				
			35.0	5631.2	3378.7	60.0%

6.3 Instrumentation Selection and Design

Instrumentation was chosen and installed to measure the temperature, relative humidity, and moisture conditions within the test walls and the climate chamber. The type and location of each sensor was chosen to measure critical conditions for the experiment, to provide redundancy, and to capture any spatial variation in the readings.

The final experimental design for the first three tests included a total of eleven sensor packages within each 4' x 8' test panel. Each package consisted of either a moisture content and temperature sensor or a relative humidity and temperature sensor. Figure 6-5 illustrates the location of both types of sensor packages within the test panels and a cross section of a typical location within a test panel is illustrated in Figure 6-6. Figure 6-7 is a photo showing typical sensor packages as installed.

In addition to these test wall sensors, additional sensors were permanently mounted on either side of the climate chamber to monitor the temperature and relative humidity. Using a data logger and multiplexer, all the data from the sensors located within the test panels and climate chamber, were measured on an hourly basis.

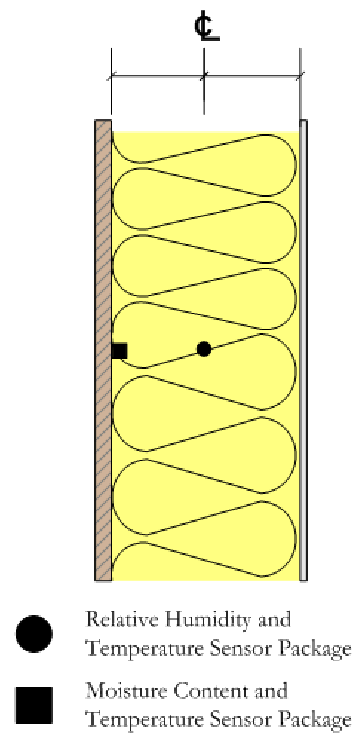

Figure 6-6: Cross-Section of a Test Panel

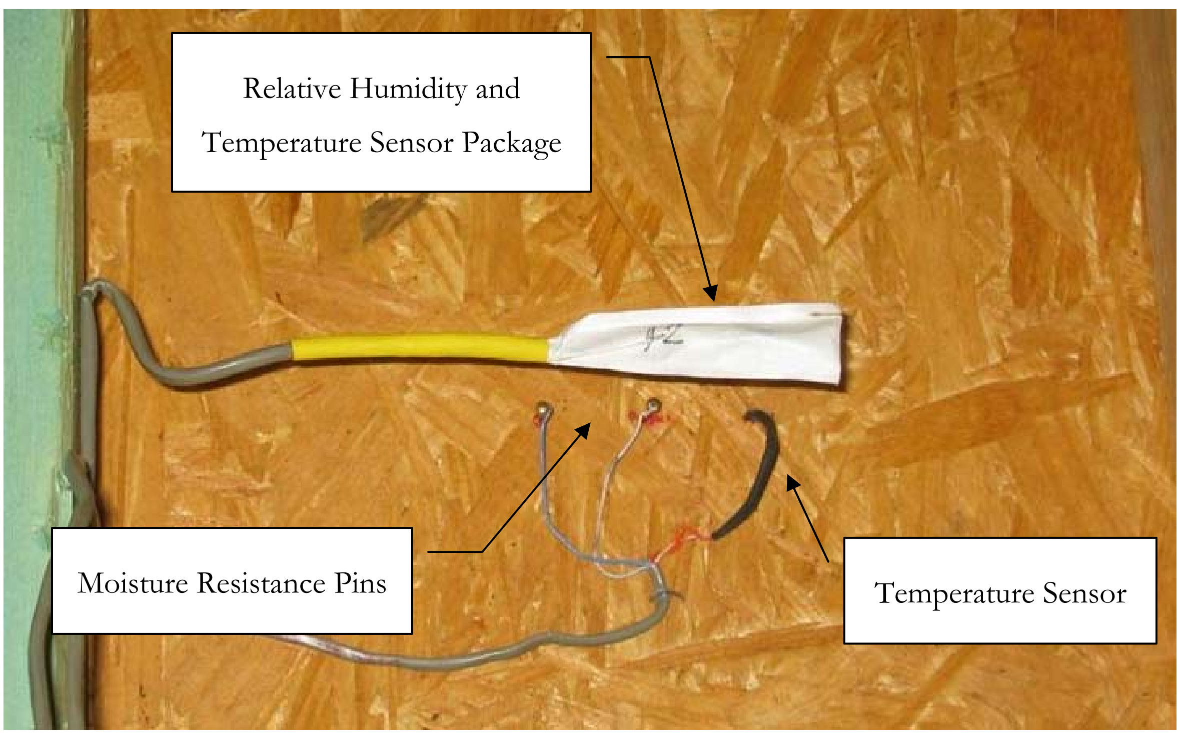

Figure 6-7: Moisture/Temperature and Relative Humidity/Temperature Sensor Packages

6.3.1 Sensors

Relative humidity was measured using a Honeywell HIH-3610-003 relative humidity sensor which has a rated ±2% accuracy over the temperature range (Figure 6-8). The temperature was measured using a Fenwal 10 kΩ thermistor with ±0.2ºC accuracy (Figure 6-9). The moisture content of wood was measured by measuring the electrical resistance across the wood using two partially insulated brass pins nailed into the wood. When deployed a relative humidity sensor was packaged alongside a temperature sensor within a Tyvek™ enclosure and moisture content sensors were installed alongside a temperature sensor. Figure 6-7 is an image of an installed relative humidity and temperature sensor package and a moisture content and temperature sensor package. For the product datasheets for both sensors refer to Appendix B.

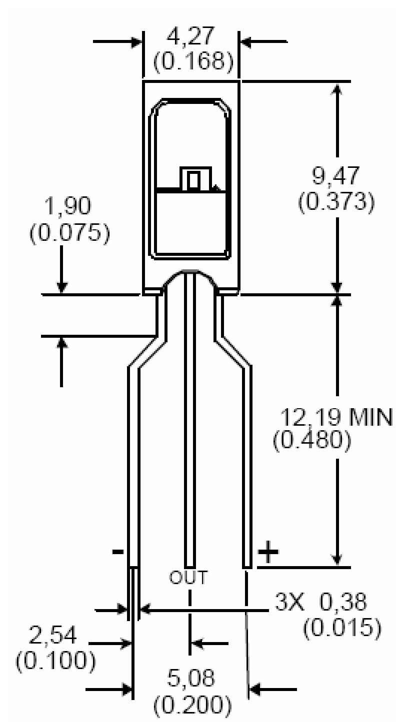

Figure 6-8: Honeywell HIH-3610-003 (Honeywell 2006)

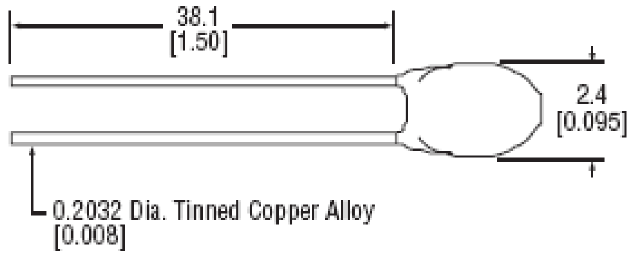

Figure 6-9: Fenwal 10 kΩ Thermistor

6.3.1.1 Relative Humidity and Temperature Sensor Package

Data collected from Honeywell HIH-3610-003 must be temperature corrected. Equation 14 is the correction used for this sensor to correct the readings for sensor temperature (Honeywell 2006).

$$RH_{Corrected} = \frac{RH_{Uncorrected}}{(1.0546 - 0.00216 \cdot T)} \qquad \text{Equation 14}$$

$RH_{Corrected}$	[%]	Temperature Corrected Relative Humidity
$RH_{Unorrected}$	[%]	Uncorrected Relative Humidity
T	[°C]	Temperature at Relative Humidity Sensor

Placing relative humidity and temperature sensors directly against the sheathing was not desirable as it can interfere with the measurements at that location. The small gap created by the sensor package between the insulation and the sheathing can allow convection loops to form which would move heat and moisture. In addition during the experiment, the very high relative humidity at this location might damage the sensor. As a result it was decided to locate the sensor in a better location near the center of the fibreglass batt insulation. Using the reading at the center of the fibreglass batt insulation it is possible to infer the relative humidity at the sheathing. This is possible because the relative humidity and temperature at the center of the Batt insulation was measured along with the temperature of the sheathing, and the vapour resistance of the fibreglass batt was assumed to be very low. The vapour permeance can be calculated from relative humidity and temperature using Equation 15. Given the temperature at the sheathing, the relative humidity behind the sheathing can be calculation from these readings using Equation 17.

$$P_w = RH_{Batt} \times 1000 \cdot \exp(52.58 - \frac{6790.5}{T_{Batt}} - 5.028 \ln T_{Batt}) \qquad \text{Equation 15}$$

$$P_{w-Batt} = P_{w-Sheating} \text{, because vapour resistance of Batt is small} \qquad \text{Equation 16}$$

$$RH_{Sheating} = \frac{RH_{Batt} \times 1000 \cdot \exp(52.58 - \frac{6790.5}{T_{Batt}} - 5.028 \ln T_{Batt})}{1000 \cdot \exp(52.58 - \frac{6790.5}{T_{Sheating}} - 5.028 \ln T_{Sheating})} \qquad \text{Equation 17}$$

P_w	[Pa]	Water Vapour Pressure
P_{ws}	[Pa]	Saturation Vapour Pressure
RH	[%]	Relative Humidity
T	[K]	Temperature

If the relative humidity was determined to be 100% or above it was assumed that condensation was forming on the back of the sheathing. This occurs because the temperature of the sheathing has dropped below that of the dew point of the air. Equation 18 was used to determine the condensation rate at the sheathing.

$$q_{\text{v-Sheating}} = \left(\frac{\Delta P_{\text{Climate}}}{R_{\text{v-Climate}}} - \frac{\Delta P_{\text{Interior}}}{R_{\text{v-Interior}}} \right)$$ Equation 18

$q_{\text{v-Sheating}}$	$[ng/(s-m^2)]$	Condensation Rate on Sheathing
R_v	$[Pa \cdot s \cdot m^2 / ng]$	Vapour Resistance
P	[Pa]	Vapour Pressure

6.3.1.2 Moisture Content and Temperature Sensor Packages

Moisture content sensors are metal pins which are nailed into a piece of wood to a given depth. The electrical resistance across the sensors can be used to determine the moisture content of the specimen. Given the electrical resistance, Equation 19 (Straube et al 2002) was used to determine the moisture content of the wood specimen.

$$\log_{10}(MC_u) = 2.99 - 2.113(\log_{10}(\log_{10}(R_w)))$$ Equation 19

MC_u	[%]	Moisture Content by Mass of Douglas-Fir at Room Temperature
R_w	$[\Omega]$	Measured Electrical Resistance of Wood

Equation 19 was developed for Douglas-Fir at room temperature. To determine the moisture content of a wood specimen which is at a temperature other than room temperature or to determine the moisture content of another species of wood other than Douglas-Fir, this moisture content from Equation 19 needs to be corrected. The temperature and species correction was performed by using the Garrahan equation (Garrahan 1998), Equation 20.

$$MC_c = \{[(MC_u + 0.567 - 0.0260 \cdot T + 0.000051 \cdot T^2)/(0.881(1.0056^T))] - b\}/a \qquad \text{Equation 20}$$

MC_u	[%]	Moisture Content by Mass of Douglas-Fir at Room Temperature
MC_c	[%]	Moisture Content by Mass (Corrected for Temperature and Species)
T	[ºC]	Temperature of Wood Specimen
a & b	[-]	Wood Species Correction Coefficients

The *a* and *b* coefficient values for typical wood species are found in Table 6-5.

Table 6-5: Species Correction Coefficient Values (Straube et al 2002)

Species	**a**	**b**
Eastern hemlock	0.904	-0.051
Sitka Spruce	0.853	0.398
Red pine	0.730	0.793
Eastern white pine	0.821	0.556
Western white pine	0.969	-0.391
Ponderosa pine	0.849	0.223
Western red cedar	1.019	-0.455
Yellow red cedar	0.922	-0.751
Alpine fir	1.070	-2.950
Norway spruce	0.702	0.818
Trembling aspen	0.910	2.750
Western white spruce	0.828	-0.621
Eastern white spruce	0.702	0.818
Lodgepole pine	0.835	-0.545
Jack pine	0.749	0.467
Balsam fir	0.900	0.350
Black spruce	0.820	-0.378
Red spruce	0.723	-0.024

The Spruce Pine Fir classification includes White Spruce, Englemann Spruce, Red Spruce, Black Spruce, Jack Pine, Lodgepole Pine, Balsam Fir, and Alpine Fir; Southern Yellow Pine includes Longleaf, Loblolly, Slash, and Shortleaf Pines. Missing from Table 6-5 are any of the species group which make up the Southern Yellow Pine classification. However, BEG recently completed an unpublished study using Southern Yellow Pine samples, *a* and *b* values were found to be 0.914 and -1.167 respectively. Further tests are planned to verify these values. In addition species correction factors for both OSB and plywood are not found in Table 6-5, again further test will be performed to determine these values.

For this study it was decided to correct the moisture contents for temperature but not for species. The decision was made because not all corrections factors are available. Future studies are planned to determine the correction factors for the missing species. However, it may not be possible to develop correction factors for OSB and plywood at very high moisture contents because above fibre saturation values are not always consistent.

6.3.1.3 HMP50

In addition to the sensors installed within the test wall assemblies there are two permanently mounted sensors were located on either side of the test wall assemblies within the climate chamber. These sensors monitor relative humidity and temperature in the climate chamber and acts as control signals for the conditions within the climate chamber. The HMP50 sensor was supplied by Campbell Scientific and is manufactured by Vaisala. The relative humidity sensor within HMP50 has a reported accuracy of between ±3% and ±5% depending on the relative humidity conditions and the temperature sensor had an accuracy of ±0.8°C. The relative humidity sensor within the HMP50 does not need to have a temperature corrections performed on it. The datasheet for this sensor can be found in Appendix B. Figure 6-10 is an image of the sensor.

Figure 6-10: HMP50 - Temperature and Relative Humidity Sensor (Campbell 2006)

6.3.2 Campbell Scientific CR10X Datalogger

The sensors within the climate chamber were connected to a Campbell Scientific CR10X datalogger system with 2 megabytes of storage (Data Sheet in Appendix C). To expand the number of sensors which may be connected to the datalogger, the CR10X was attached to a multiplexer. This allowed every sensor within the climate chamber to be connected to the system. Originally the system was directly connected to a computer which was used to download the data from the datalogger. Later in the research a NL100 network interface was attached to the datalogger to allow remote access. Figure 6-11 is an image of the data logging system.

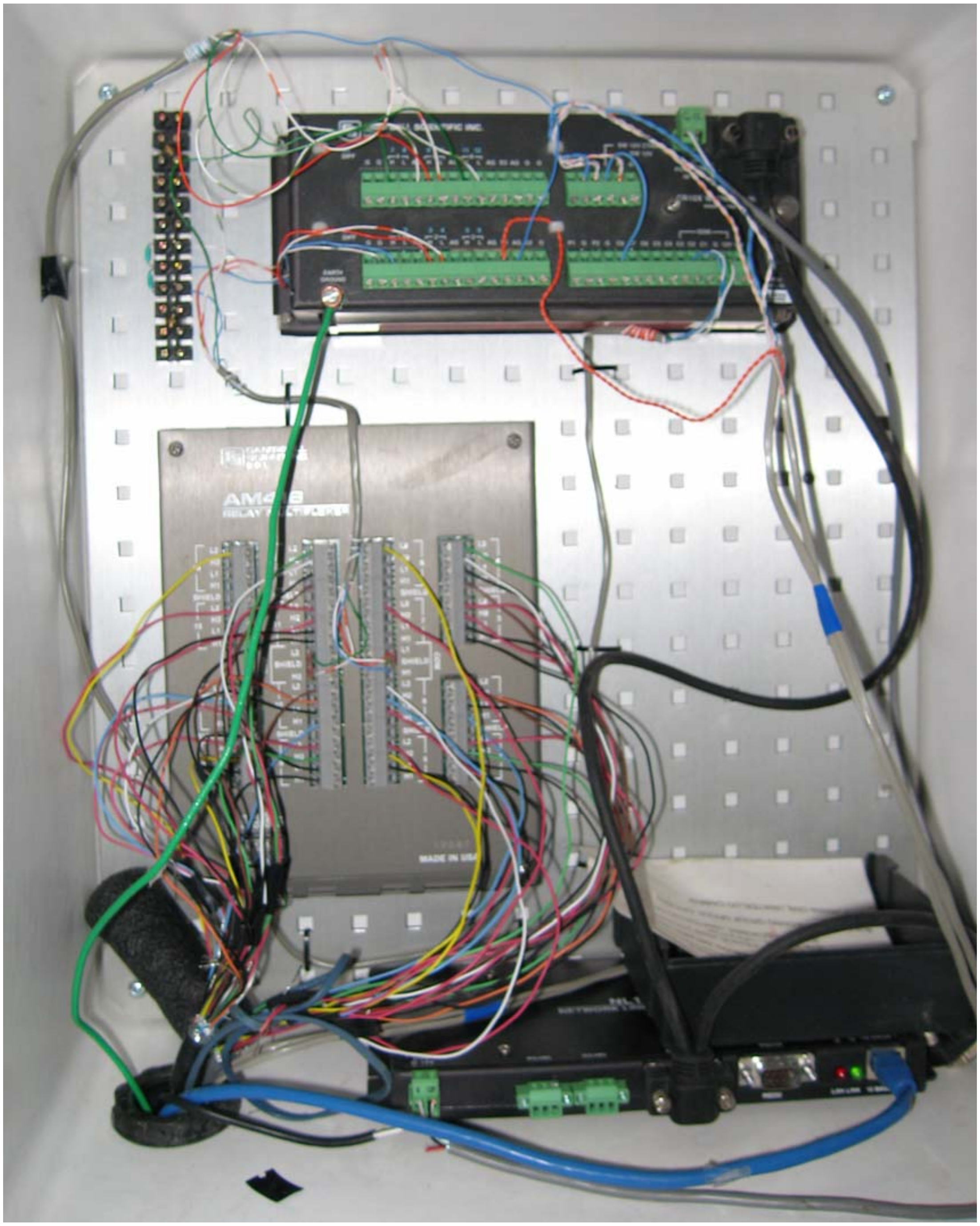

Figure 6-11: CR10X Datalogger with an AM416 Multiplexer and a NL100 Network Interface

6.3.3 Data Analysis Database

Early in the experiment it was determined that, given the large amount of data to be collected, it would be beneficial to have a program which would streamline the process of storing, maintaining, and analysing the data. After careful consideration it was determined that the Microsoft Access Database would be the best suited for the platform to develop the tool. Some of the reasons for this decision included user friendliness, graphing capability, wide available of the program, and compatibility with the rest of the Microsoft family of products.

Therefore, over the last two years a customized database application was developed to meet the previously stated requirements. As a testimony to the benefit of this program the customized database has been used on numerous different projects to dramatically speed up data analysis. The completed program directly interfaces with output data from data loggers used in a range of laboratory and field studies at BEG. The exported data is stored and processed in the database, allows for easy comparison of the sensors, and even the ability to export graphs and data to other programs.

6.4 Tracking the Performance of the Test Wall Assemblies

The performance of the test wall was tracked visually by weekly inspections of each of the eight test ports. Every week the test ports were opened and examined for mould growth using an 8 power loupe. Using Viitanen's mould index the amount of mould growth was quantified and given a rating between 0 and 6 depending on the amount of mould growth. At the same time as the visual inspection each of the eight test ports were photographed. Photographs were taken by placing the test ports on a specially constructed stand which was located on one side of the chamber. The camera was mounted on a tripod which was located at the exact same sport every week. Both these steps ensured repeatable results. In addition to the previous precautions, in the later tests special marks were placed on the test ports themselves to allow for a better spatial reference for the comparison of the test ports over the duration of the tests.

It was necessary to remove the test ports in order to inspect the amount of mould growth on the sheathing and framing within the test walls. However, by opening the test ports and examining the wall cavity the conditions within the wall cavity are affected and the mould growth itself may be affected. Therefore, when the test ports were opened it was necessary to minimize the amount of disturbance to the tests. This was accomplished by limiting the visual inspections to a weekly basis and by conducting them as quickly as possible. Also only one of the eight test ports were opened at one time. Given the ability of the chamber to quickly return to the appropriate conditions, it can be assumed that the conditions behind the sheathing would also have returned quickly to the desired conditions.

6.5 Maintenance

The climate chamber was not completely automated and along with the inspections and photographs, the climate chamber required maintenance every few days. This maintenance included the addition of water to the humidifiers, the removal of water from the dehumidifiers, and the addition of water to the chiller.

6.6 Sources of Error

Efforts were made to minimize measurement errors by installing redundant sensors and by choosing instruments of relatively high accuracy. However, sources of error in the experimental program were still present, as described below.

1. Accuracy of instrumentation, including the relative humidity sensor, temperature sensor, moisture content pins, and data logger. The error was minimized by selecting sensors and equipment which have a high accuracy.
2. The location of the sensors had some effect on the measurement accuracy. Relative humidity sensors were to be placed mid-thickness in the batt insulation, but some variations were likely during installation. Multiple sensors were used within a wall, thus allowing correlation. Moisture content pins could have been installed at different depths; however, a depth gauge was used to ensure consistent installation.
3. Human error, when visually inspecting the test ports the observations may not be consistent. This was minimized by having the same individual inspect the test ports throughout most of the experimental study, and having a well defined visual scale.

7 Experimental Results

7.1 Borate Concentration

The concentration of borate treatment within the treated lumber was determined by sending samples of each type of lumber to U.S. Borax Inc. For the 2" x 4" lumber, which included the Douglas Fir, Spruce Pine Fir, and Southern Yellow Pine, a sample was taken from near the end of the original 10' long pieces of lumber to avoid edge effects. For the analysis of the sheathing 3 samples were taken from different locations, Figure 7-1 illustrates the locations where the samples were taken. The results from the analysis which determined the borate concentrations were averaged and can be found in Table 7-1. For complete results of the analysis refer to Appendix C.

Table 7-1: Concentration of Boron and/or Zinc Displayed in Either Units of ppm or Boric Acid Equivalent (BAE)

Species	ppm B	ppm Zn	% BAE(B)	%BAE(Zn)
OSB	65.4	130.1	0.91	0.95
Plywood	209.1	-	1.44	-
Douglas-Fir - Core	70.4	-	1.61	-
Douglas-Fir - Outside	960.9	-	4.46	-
Spruce Pine Fir - Core	2.9	-	0.07	-
Spruce Pine Fir - Outside	453.7	-	2.25	-
Southern Yellow Pine - Core	106.5	-	4.65	-
Southern Yellow Pine - Outside	854.0	-	2.83	-

OSB, Plywood, and all the different types of dimensional lumber are very different products and applying borate treatment affects each product differently. Comparing OSB with plywood solely based upon the concentration is difficult because the material properties of both materials are very different and the borate treatments used are also different. However, the Boric Acid Equivalent (BAE) does indicate there is less treatment within the OSB than there is within the plywood. The concentration of boron and zinc within the treated lumber is presented as a record for comparison to future studies when trying to recreate similar test conditions.

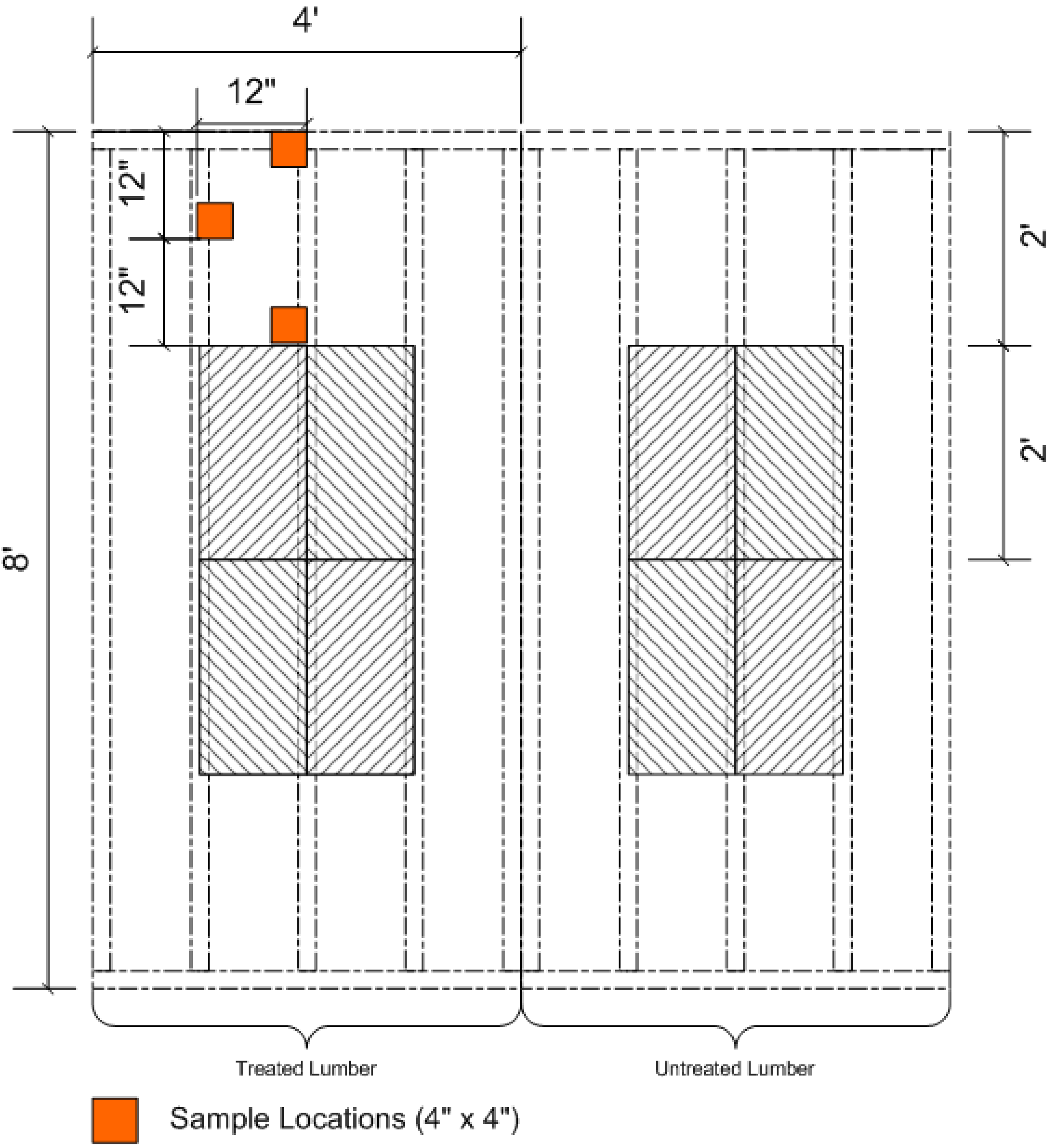

Figure 7-1: Location of Sample Used for Borate Concentration Analysis

7.2 Chamber Commissioning Test

A commissioning test was undertaken to determine the effectiveness of the equipment in controlling the conditions within the climate chamber and test panels. Only standard framing lumber (3/8" plywood and standard OSB from local suppliers) was used in the commissioning test panels. The commissioning test began on Monday August 9, 2004, after placing the commissioning test panels within the climate chamber. The commissioning test was completed on Friday September 30, 2004.

During the inspection of the test ports on Tuesday September 7, 2004, extensive mould growth was observed on the test ports along with the observation of liquid water. Images of the mould growth after disassembly of the commissioning test are shown in Figure 7-2 and Figure 7-3. Early on during the commissioning test the relative humidity at the back the sheathing at some locations exceeded 100%, and therefore condensation conditions existed. As liquid water is deposited as a result of condensation the moisture content of the wood sheathing was likely to be higher than the target high RH levels. Hence, the mould growth observed was likely the result of this highly favourable (for mould growth) condition. After discovering this condensation problem the appropriate modifications were made and the relative humidity and temperature conditions were modified to eliminate condensation on September 21, 2004.

Figure 7-2: Image of Mould Growth on the Wall Assembly used in the Commissioning Test

Figure 7-3: Image of Mould Growth at end of Commissioning Test

Higher RH and subsequent condensation conditions occurred in the OSB panel compared to the plywood portion of the test wall assembly. This was due to the lower vapour permeance of the OSB sheathing relative to the plywood sheathing. The plywood sheathing allowed water vapour to travel through so easily that the relative humidity within the fibre glass insulation and on the back of the sheathing remained significantly below that of the relative humidity in the OSB panel. This required the change in design of the test panels which was described previously.

In subsequent tests, the relative humidity conditions were monitored very closely to ensure condensation conditions only occurred when desired at the appropriate locations. The commissioning test showed that the climate chamber was capable of providing very stable conditions (+/- 1%RH and +/-0.5 C). Figure 7-4 illustrates the stability of the relative humidity and temperature on either side of the chamber after the modifications were made. The anomalies in the reading illustrated in Figure 7-4 occur when the door to the climate chamber is opened and the climate chamber tries to return to the desired conditions. The ability of the climate chamber to grow mould was also demonstrated through the commissioning test. Given the suggested improvements to the experimental design and construction, the climate chamber and wall assemblies were proven capable of running the study within the desired conditions producing the desired results.

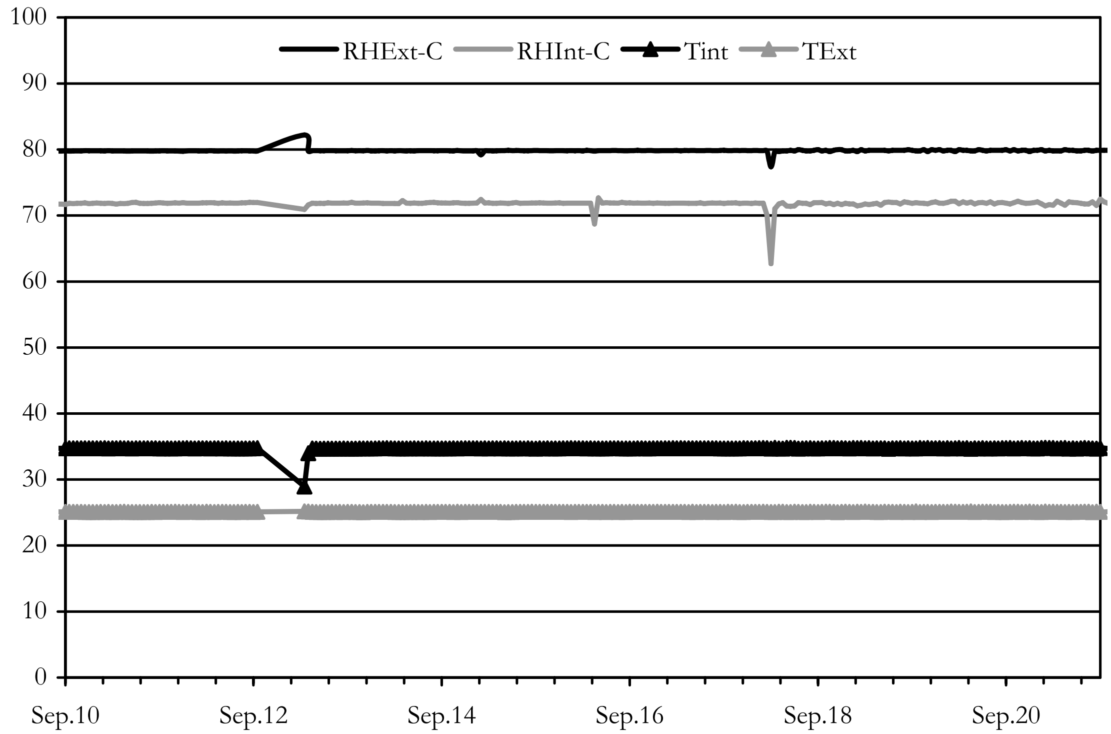

Figure 7-4: Demonstration of the Stability of Temperature and Relative Humidity

7.3 Test Number 1

The first of the planned climate chamber tests began Wednesday October 13, 2004, and was completed on Wednesday February 23, 2005, a duration of 19 weeks.

7.3.1 Timeline

A timeline for the conditions in the interior side of the climate chamber can be seen in Figure 7-5. Test Number 1 has been broken into 6 major events. From October 13, 2004, to December 8, 2004, the relative humidity of the interior side climate chamber was varied in an attempt to produced 95% relative humidity conditions at the interstitial facing side of the sheathing. On December 8, 2005, the interstitial facing side of the sheathing conditions stabilized at approximately 95%. These conditions were achieved by maintaining the interior side of the climate chamber at a relative humidity of 53.5%. These conditions were maintained until January 4, 2005, when it was decided this test was not achieving its original goal of demonstrating mould growth, To promote accelerated growth, condensation conditions were imposed on January 4, 2005, the relative humidity on the interior side of the climate chamber was increased until condensation conditions were reached on the interstitial facing sheathing conditions. These conditions were maintained until January 17, 2005, when the relative humidity conditions in the interior side of the climate chamber were again lowered to 53.5%. These conditions were maintained until February 4, 2005, at which point it was decided to again create condensation conditions on the interstitial facing sheathing conditions. Condensation conditions were maintained until February 16, 2005, at which time the relative conditions in the interior side of the climate chamber were lowered to 53.5% for the remainder of the test which was completed on February 23, 2005. For the entire test the climate side of the climate chamber was maintained at 26ºC and 80% RH, and the temperature of the interior side of the climate chamber was maintained at 35ºC.

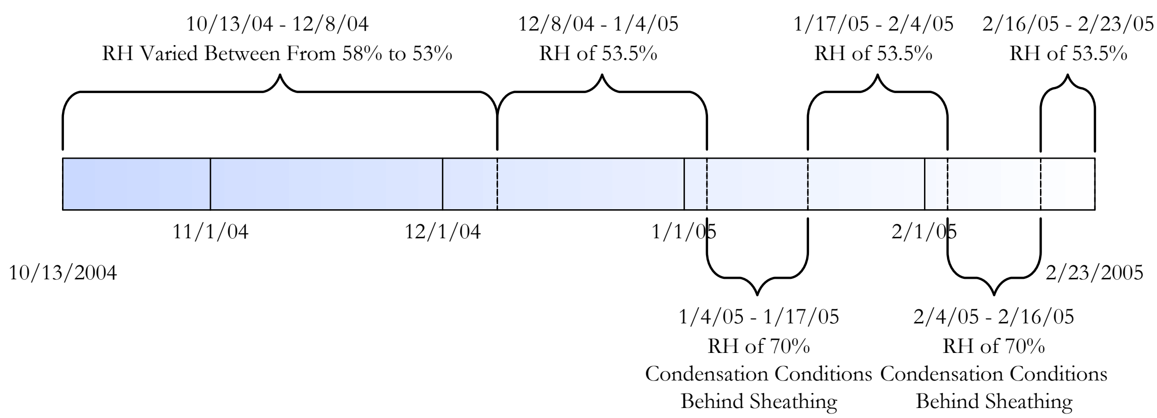

Figure 7-5: Timeline for Test Number 1 – Relative Humidity Conditions on Interior Side of the Climate Chamber (Climate Side Conditions of the Climate Chamber Were Maintained at 26ºC and a Relative Humidity of 80%)

7.3.2 Data Collected

Graphical summaries of the results within the test panels and climate chamber were generated to aid data analysis. Figure 7-6 illustrates the relative humidity and temperature conditions on either side of the climate chamber which were maintained during the entire test. The only condition which was varied was the relative humidity maintained on the interior side of the climate chamber. The relative humidity on the interior side of the climate chamber was used to control the conditions behind the sheathing which is evident when comparing Figure 7-6 to Figure 7-7 (relative humidity at the back of the sheathing). Figure 7-8 illustrates the rate of condensation on the interstitial side of the sheathing when conditions at the back of the sheathing reach a relative humidity of 100%. The moisture content of wooden materials within the wall assembly is shown in Figure 7-9 thru Figure 7-12.

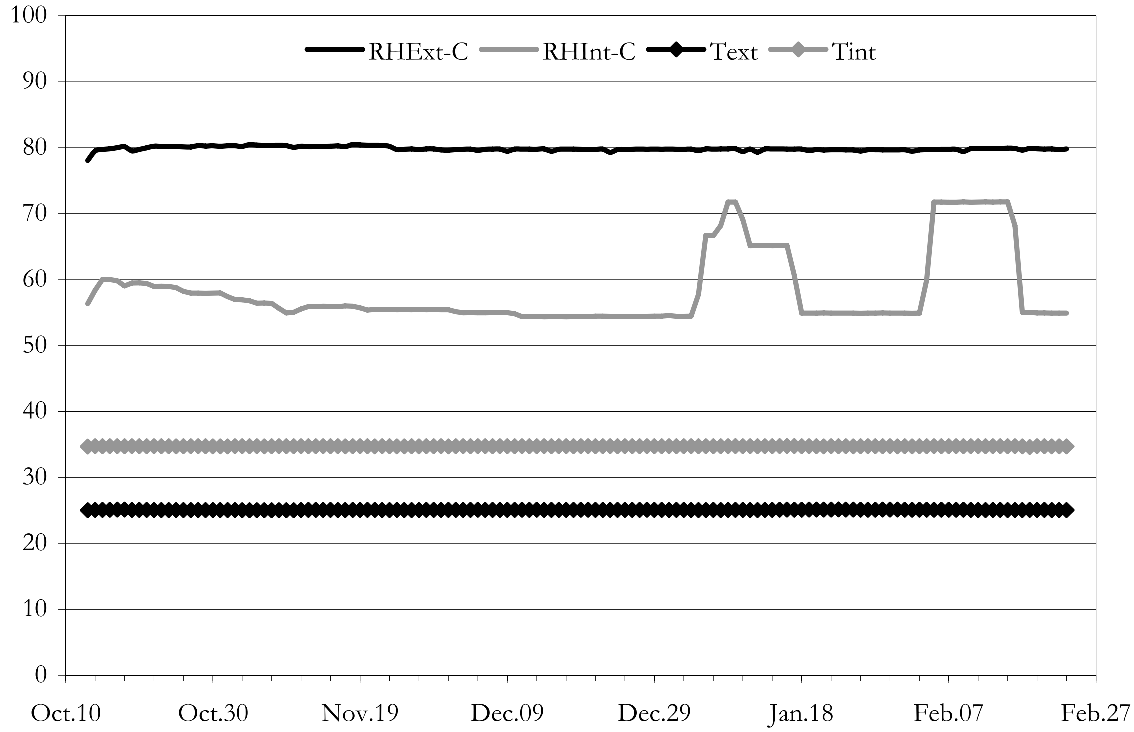

Figure 7-6: Temperature (°C) and Relative Humidity (%RH) Conditions from the Climate Chamber in Test Number 1

RHExt-C	Relative Humidity Climate Side
RHInt-C	Relative Humidity Interior Side
Text	Temperature Climate Side
Tint	Temperature Interior Side

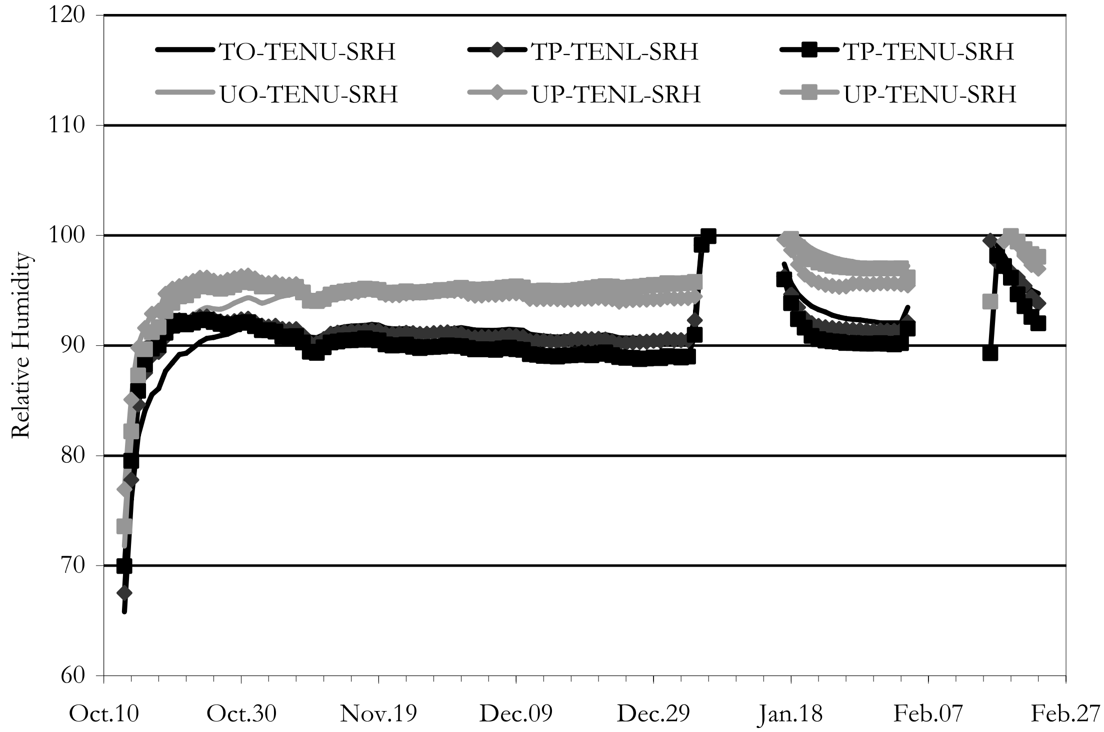

Figure 7-7: Relative Humidity at Back of Sheathing in Test Number 1

TO-TENU-SRH	Treated OSB in Upper Quadrant
TP-TENL-SRH	Treated Plywood in Lower Quadrant
TP-TENU-SRH	Treated Plywood in Upper Quadrant
UO-TENU-SRH	Untreated OSB in Upper Quadrant
UP-TENL-SRH	Untreated Plywood in Lower Quadrant
UP-TENU-SRH	Untreated Plywood in Upper Quadrant

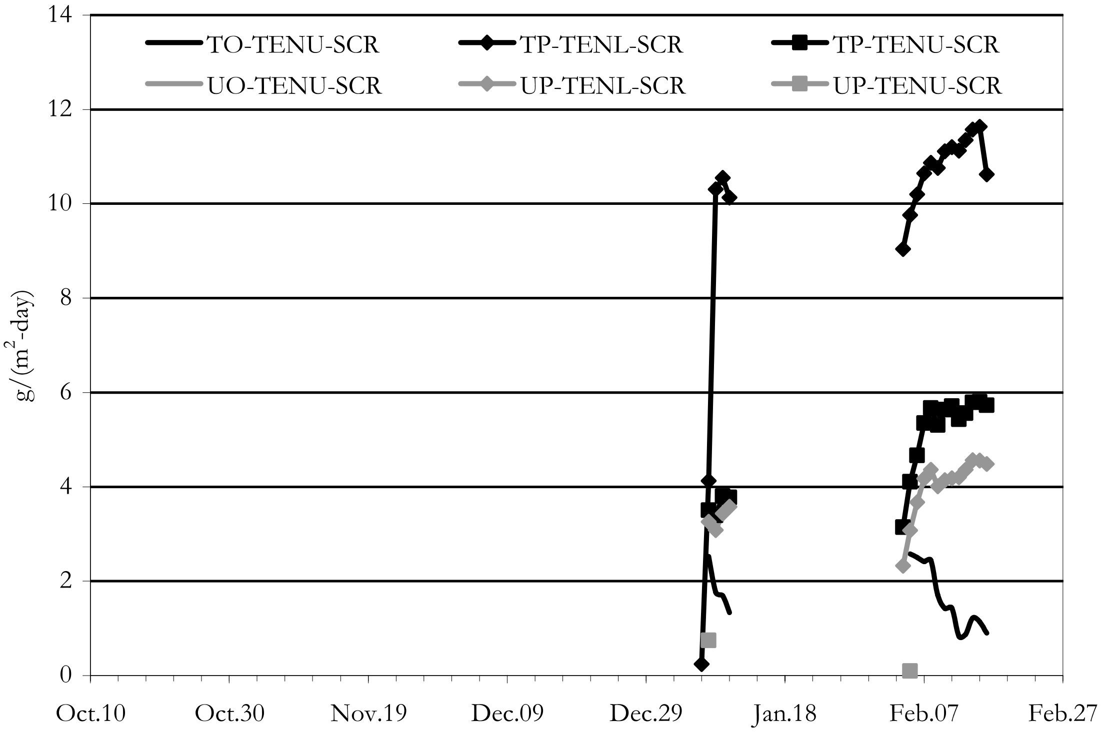

Figure 7-8: Condensation Rate on Back of Sheathing in Test Number 1

TO-TENU-SRH	Treated OSB in Upper Quadrant
TP-TENL-SRH	Treated Plywood in Lower Quadrant
TP-TENU-SRH	Treated Plywood in Upper Quadrant
UO-TENU-SRH	Untreated OSB in Upper Quadrant
UP-TENL-SRH	Untreated Plywood in Lower Quadrant
UP-TENU-SRH	Untreated Plywood in Upper Quadrant

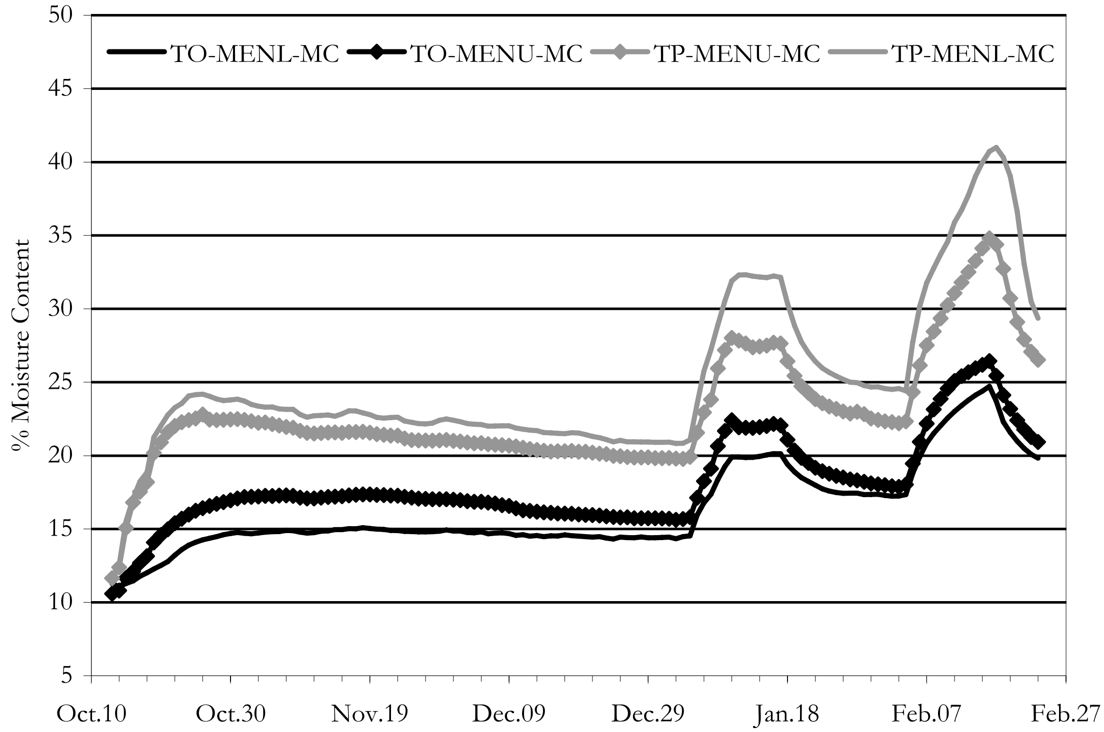

Figure 7-9: Moisture Content of Treated Sheathing in Test Number 1

TO-MENL-MC	Treated OSB in Lower Quadrant
TO-MENU-MC	Treated OSB in Upper Quadrant
TP-MENU-MC	Treated Plywood in Upper Quadrant
TP-MENL-MC	Treated Plywood in Lower Quadrant

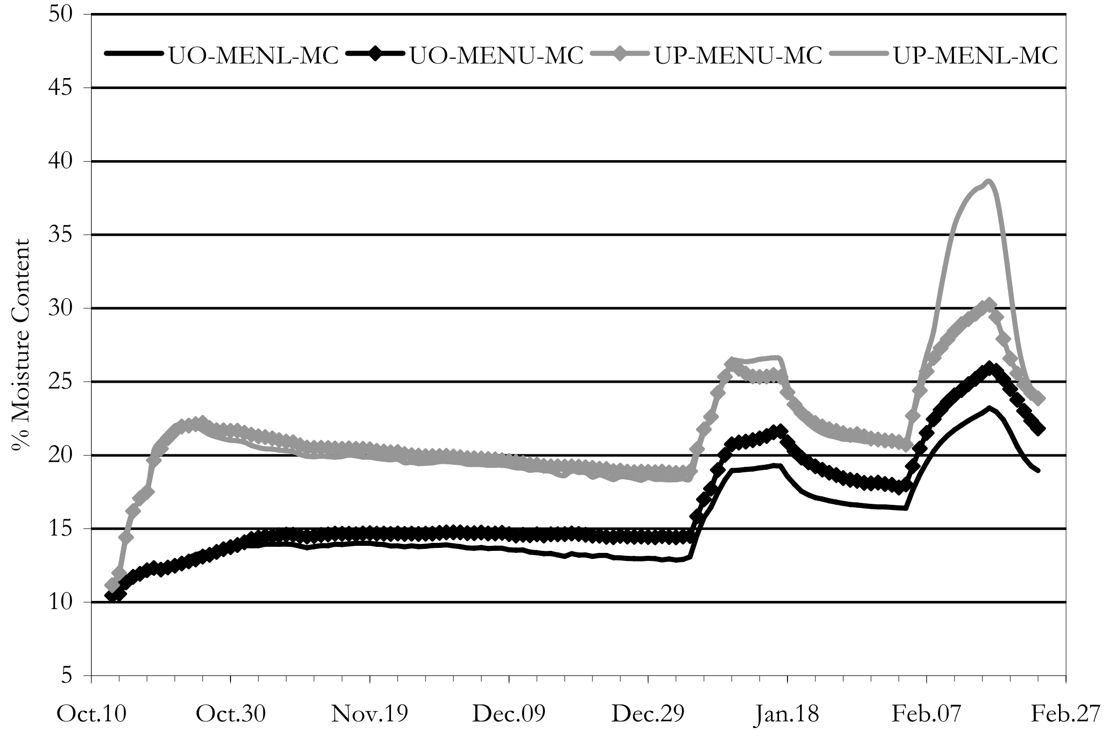

Figure 7-10: Moisture Content of Untreated Sheathing in Test Number 1

UO-MENL-MC	Untreated OSB in Lower Quadrant
UO-MENU-MC	Untreated OSB in Upper Quadrant
UP-MENU-MC	Untreated Plywood in Upper Quadrant
UP-MENL-MC	Untreated Plywood in Lower Quadrant

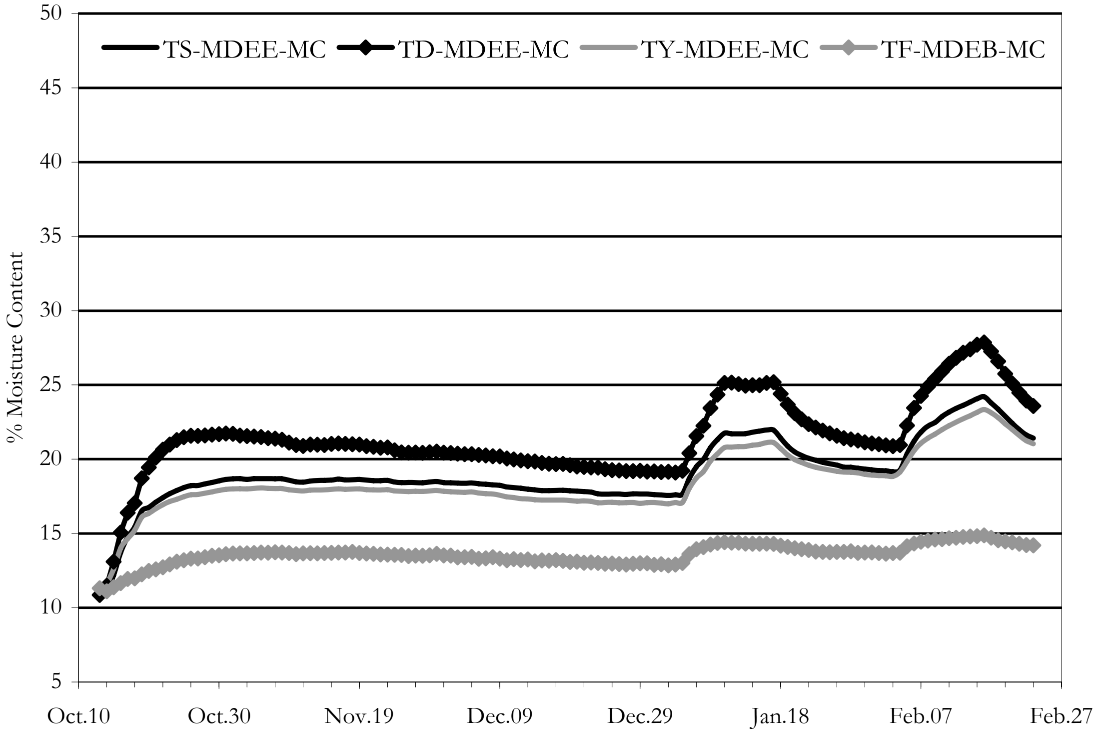

Figure 7-11: Moisture Content of Treated Dimensional Lumber in Test Number 1

TS-MDEE-MC	Treated Spruce Pine Fir
TD-MDEE-MC	Treated Douglas Fir
TY-MDEE-MC	Treated Southern Yellow Pine
TF-MDEB-MC	Bottom Plate

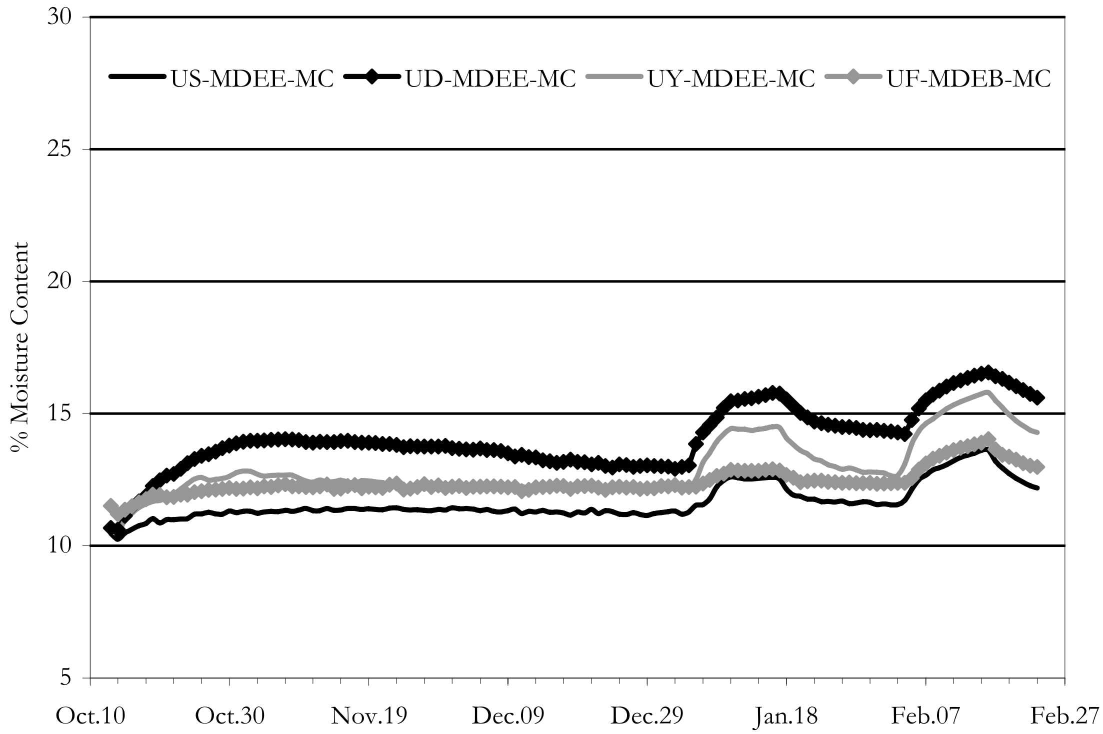

Figure 7-12: Moisture Content of Untreated Dimensional Lumber in Test Number 1

US-MDEE-MC	Untreated Spruce Pine Fir
UD-MDEE-MC	Untreated Douglas Fir
UY-MDEE-MC	Untreated Southern Yellow Pine
UF-MDEB-MC	Bottom Plate

7.4 Test Number 2

The second of the planned climate chamber tests began Thursday March 9, 2005 and was completed on Monday July 11, 2005, a duration of 18 weeks.

7.4.1 Timeline

A timeline for the conditions in the interior side of the climate chamber is presented in Figure 7-13. Test Number 2 was broken into 2 major events. From March 9, 2005, to April 4, 2005, the interior side climate chamber was maintained above a relative humidity of 70% to produce condensation on the interstitial side of the sheathing until the moisture content of the sheathing stabilized. On April 4, 2005 the moisture content of the sheathing stabilized and so the relative humidity on the interior side of the climate chamber was lower to 55% for the remainder of the experiment. For the entire test the climate side of the climate chamber were maintained at temperature of 26ºC and 80% RH, and the temperature of the interior side of the climate chamber was maintained at 35ºC.

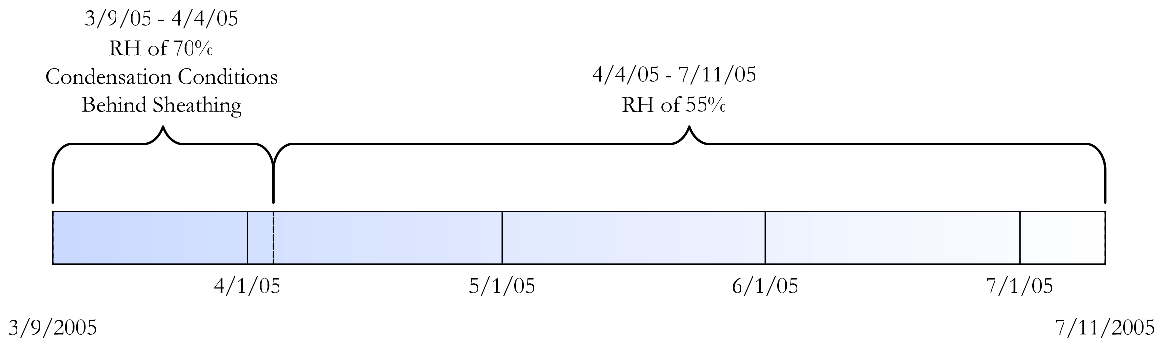

Figure 7-13: Timeline for Test Number 2 – Relative Humidity Conditions on Interior Side of the Climate Chamber (Climate Side Conditions of the Climate Chamber Were Maintained at 26ºC and Relative Humidity of 80%)

7.4.2 Data Collected

The relative humidity and temperature conditions on either side of the climate chamber are plotted in Figure 7-14. The only condition which was varied was the relative humidity on the interior side of the climate chamber. It is evident that the relative humidity on the interior side of the climate chamber directly influenced the conditions behind the sheathing when comparing Figure 7-14 to Figure 7-15. Figure 7-16 illustrates the rate of condensation on the interstitial side of the sheathing when conditions at the back of the sheathing reach a relative humidity of 100%. The moisture content of wooden materials within the wall assembly is shown in Figure 7-17 thru Figure 7-20.

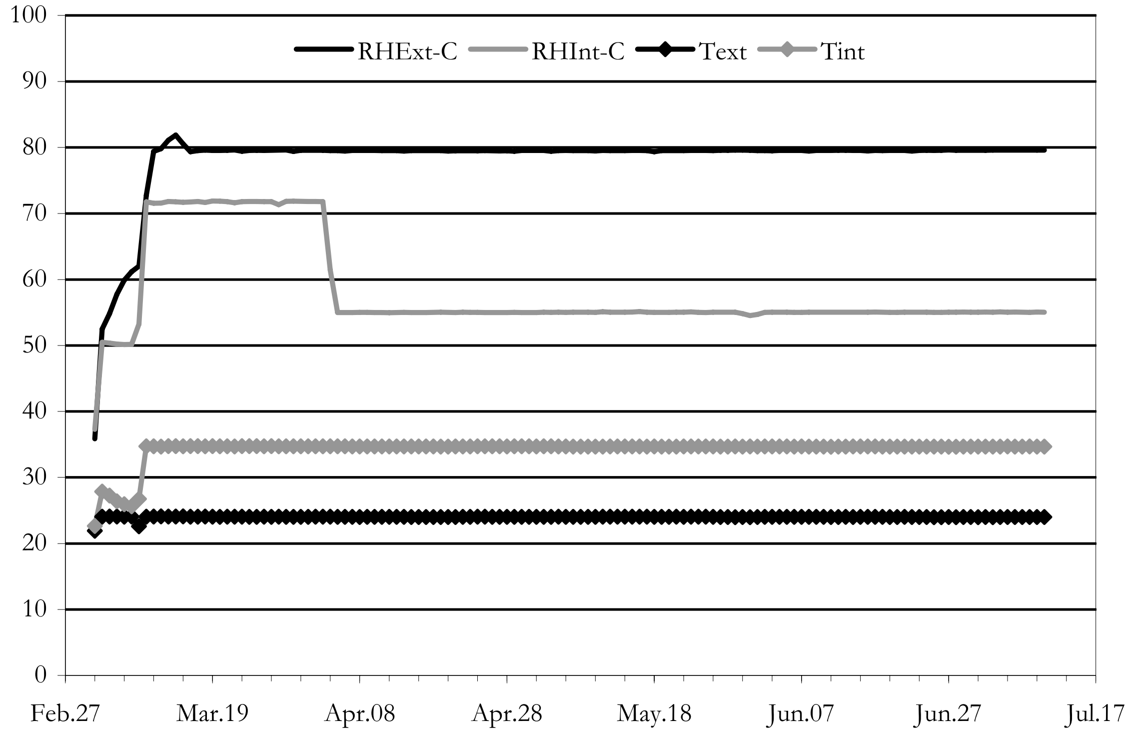

Figure 7-14: Temperature (°C) and Relative Humidity (%RH) Conditions from the Climate Chamber in Test Number 2

RHExt-C	Relative Humidity Climate Side
RHInt-C	Relative Humidity Interior Side
Text	Temperature Climate Side
Tint	Temperature Interior Side

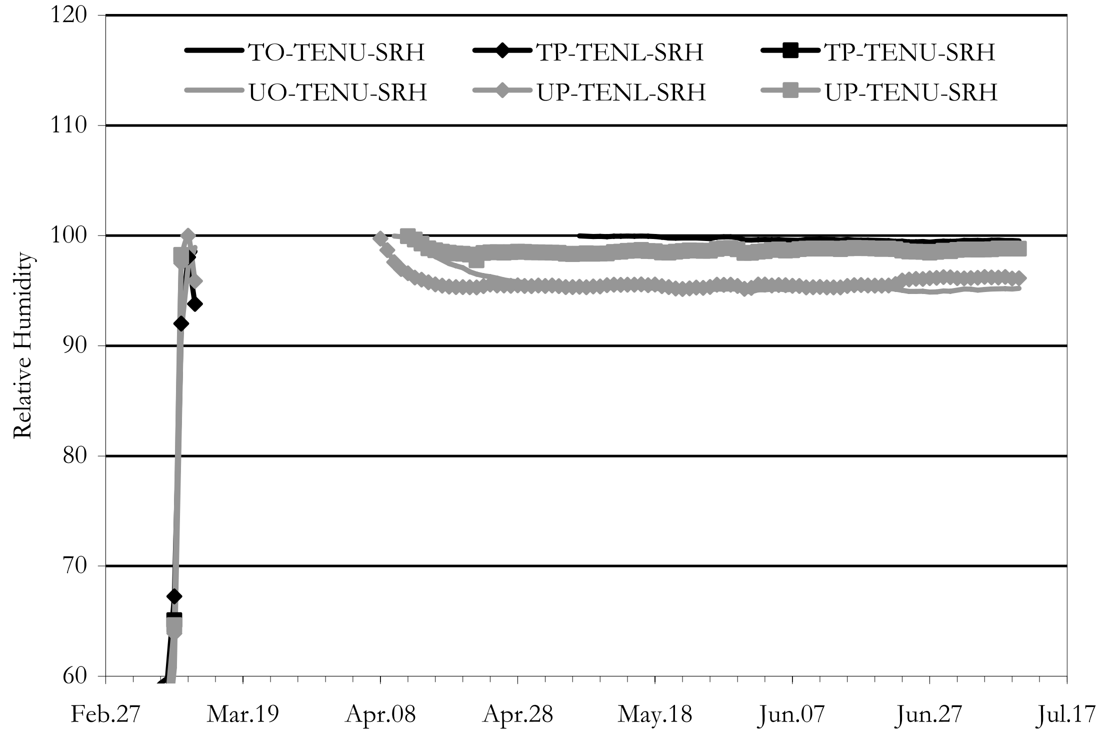

Figure 7-15: Relative Humidity at Back of Sheathing in Test Number 2

TO-TENU-SRH	Treated OSB in Upper Quadrant
TP-TENL-SRH	Treated Plywood in Lower Quadrant
TP-TENU-SRH	Treated Plywood in Upper Quadrant
UO-TENU-SRH	Untreated OSB in Upper Quadrant
UP-TENL-SRH	Untreated Plywood in Lower Quadrant
UP-TENU-SRH	Untreated Plywood in Upper Quadrant

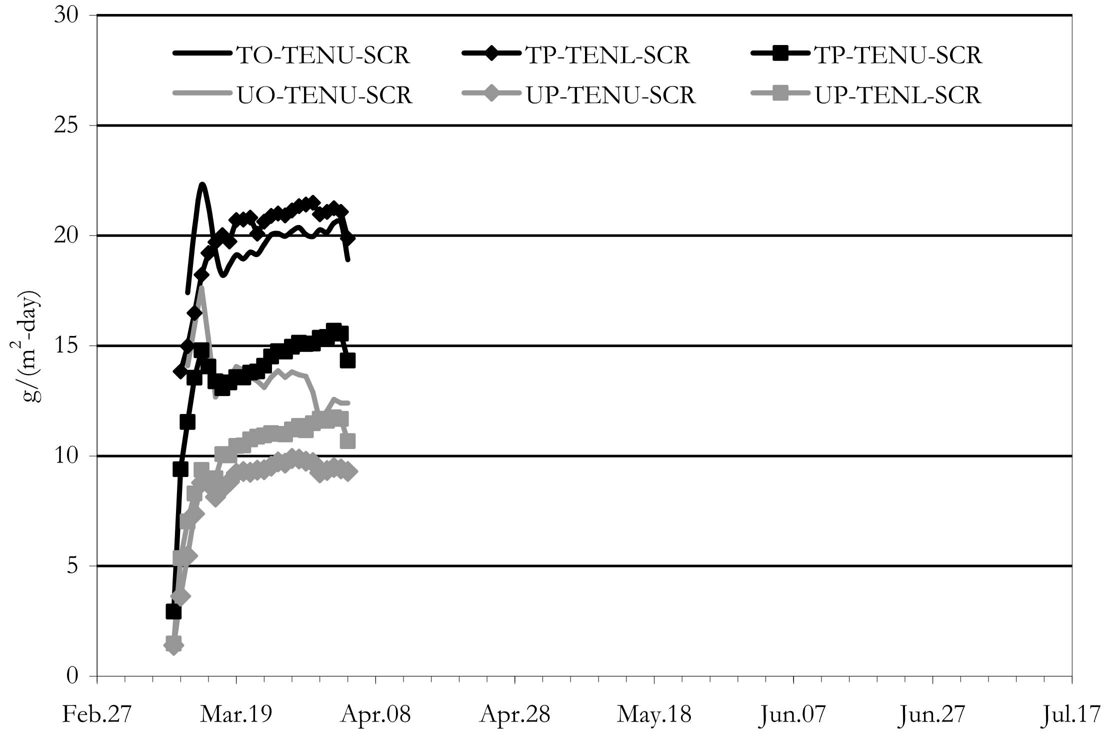

Figure 7-16: Condensation Rate on Back of Sheathing in Test Number 2

TO-TENU-SRH	Treated OSB in Upper Quadrant
TP-TENL-SRH	Treated Plywood in Lower Quadrant
TP-TENU-SRH	Treated Plywood in Upper Quadrant
UO-TENU-SRH	Untreated OSB in Upper Quadrant
UP-TENL-SRH	Untreated Plywood in Lower Quadrant
UP-TENU-SRH	Untreated Plywood in Upper Quadrant

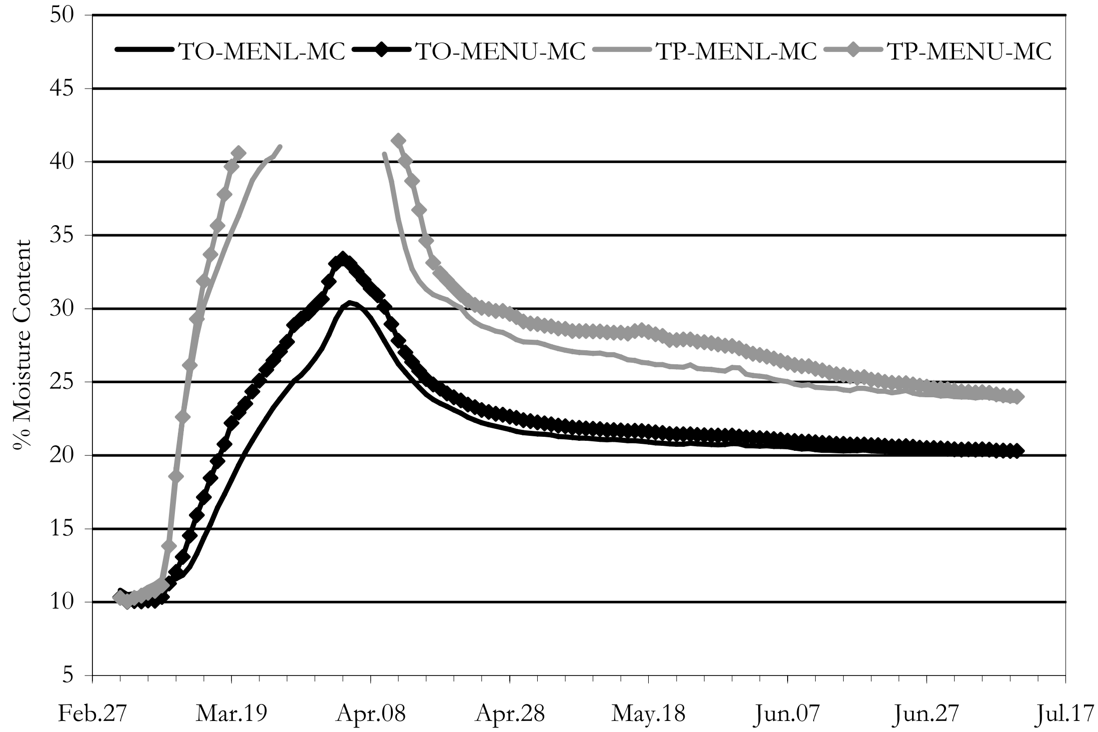

Figure 7-17: Moisture Content of Treated Sheathing in Test Number 2

TO-MENL-MC	Treated OSB in Lower Quadrant
TO-MENU-MC	Treated OSB in Upper Quadrant
TP-MENU-MC	Treated Plywood in Upper Quadrant
TP-MENL-MC	Treated Plywood in Lower Quadrant

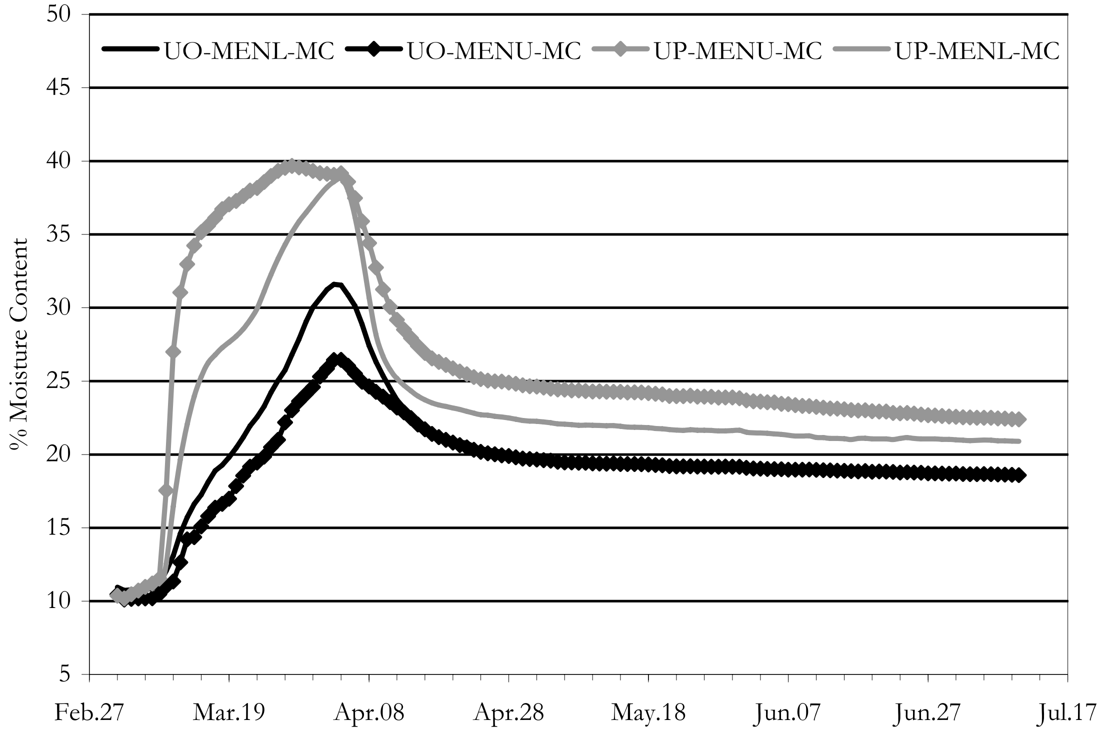

Figure 7-18: Moisture Content of Untreated Sheathing in Test Number 2

UO-MENL-MC	Untreated OSB in Lower Quadrant
UO-MENU-MC	Untreated OSB in Upper Quadrant
UP-MENU-MC	Untreated Plywood in Upper Quadrant
UP-MENL-MC	Untreated Plywood in Lower Quadrant

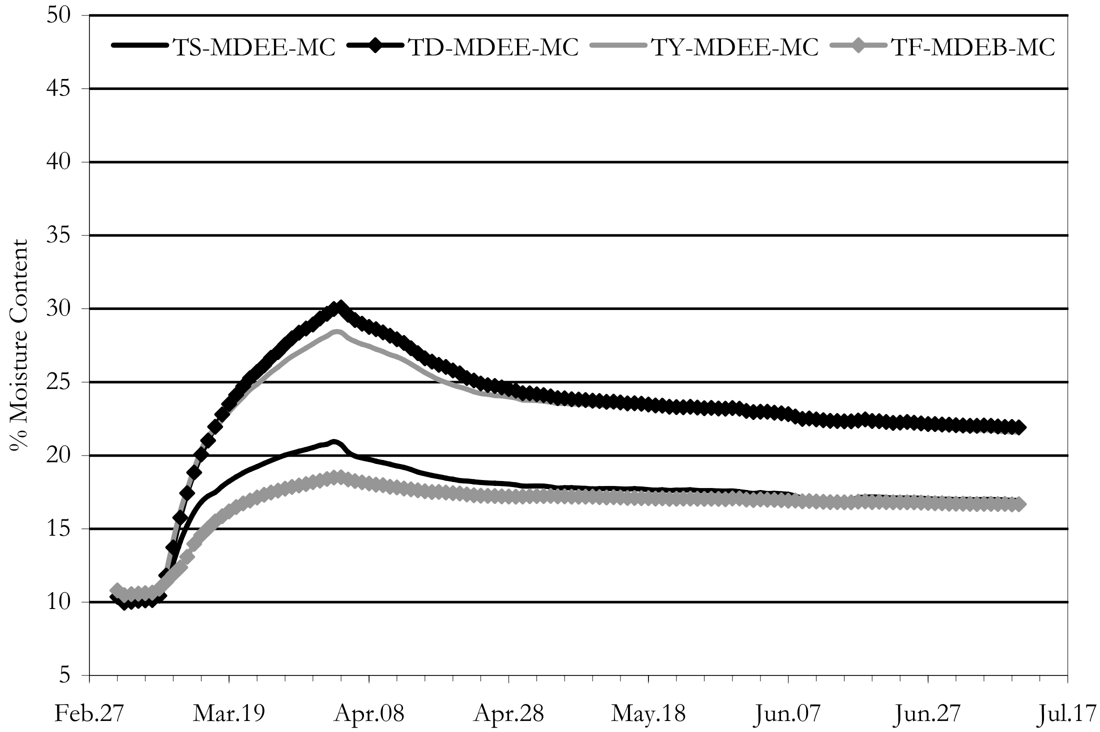

Figure 7-19: Moisture Content of Treated Dimensional Lumber in Test Number 2

TS-MDEE-MC	Treated Spruce Pine Fir
TD-MDEE-MC	Treated Douglas Fir
TY-MDEE-MC	Treated Southern Yellow Pine
TF-MDEB-MC	Bottom Plate

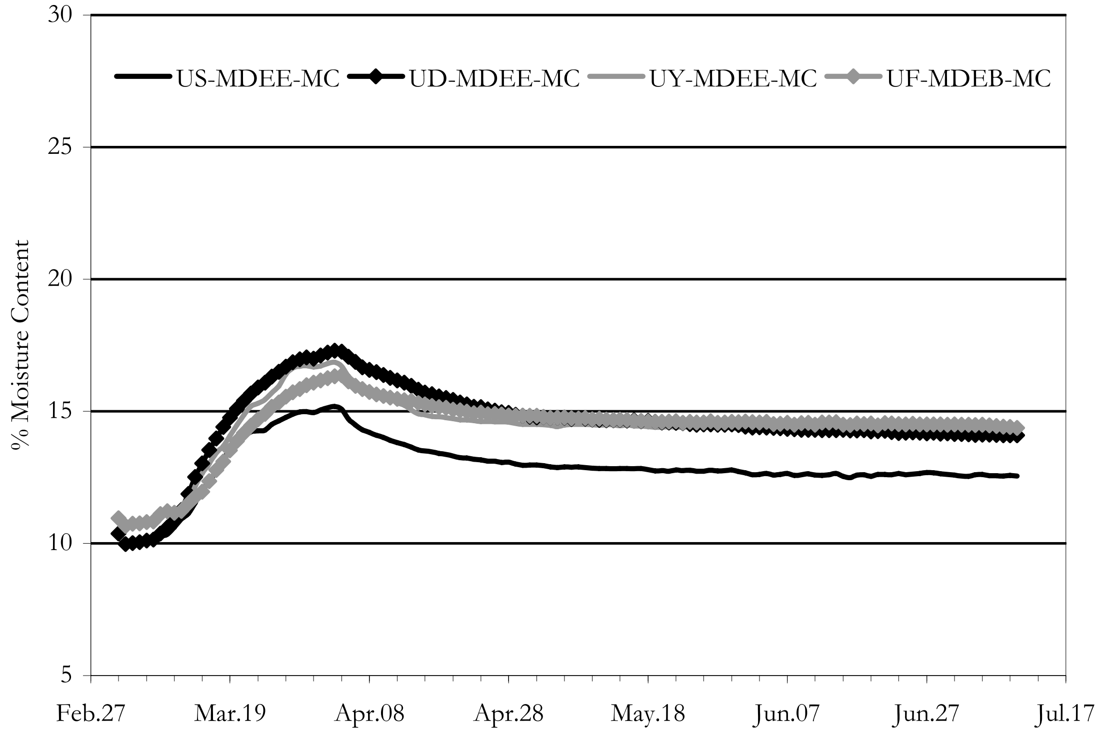

Figure 7-20: Moisture Content of Untreated Dimensional Lumber in Test Number 2

US-MDEE-MC	Untreated Spruce Pine Fir
UD-MDEE-MC	Untreated Douglas Fir
UY-MDEE-MC	Untreated Southern Yellow Pine
UF-MDEB-MC	Bottom Plate

7.5 Test Number 3

The third of the planned climate chamber tests began Wednesday September 28, 2005 and was completed on Sunday January 15, 2005, a duration of 16 weeks.

7.5.1 Timeline

Unlike the previous tests the temperature conditions were varied throughout test number 3. Furthermore, unlike previous tests the climate side conditions were varied. From September 28, 2005, to January 15, 2005, on a daily basis the temperature on the interior side of the climate chamber was varied between 20ºC and 30ºC degrees, and respectively the relative humidity was maintained at either 80% or 70%. For 8 hours of each day the conditions at the back of the sheathing were maintained at 20ºC and 100% RH and for the remaining 16 hours of each day the conditions were 30ºC and 80% RH. For the entire test the conditions on the climate side of the climate chamber conditions were maintained at a temperature of 35ºC and a relative humidity of 67%.

7.5.2 Data Collected

The relative humidity and temperature conditions either side of the climate chamber were maintained at during the entire test are shown in Figure 7-21 and Figure 7-22. The only condition which was varied was the temperature on the climate side which also affected the relative humidity on the climate side of the climate chamber. The variations in temperature did affect the conditions behind the sheathing which is evident when comparing Figure 7-21 and Figure 7-22 to Figure 7-23. Figure 7-24 illustrates the rate of condensation on the interstitial side of the sheathing. The moisture content of wooden materials within the wall assembly is shown in Figure 7-25 thru Figure 7-28. Within Figure 7-27 there is an anomaly in the reading as the moisture content within the framing reaches almost 40%. This was a result of water leaking onto the floor of the chamber from the fan coil unit. However, the water leak was limited to the floor and the bottom plate of the wall assembly and did not negatively affect the results. Maintaining the relative humidity of the climate side of the climate chamber was difficult and was made even more difficult with the failure of the humidifying equipment on December 22nd, 2005. As a result the moisture contents of the materials within the wall assembly were affected, stabilizing at lower moisture contents.

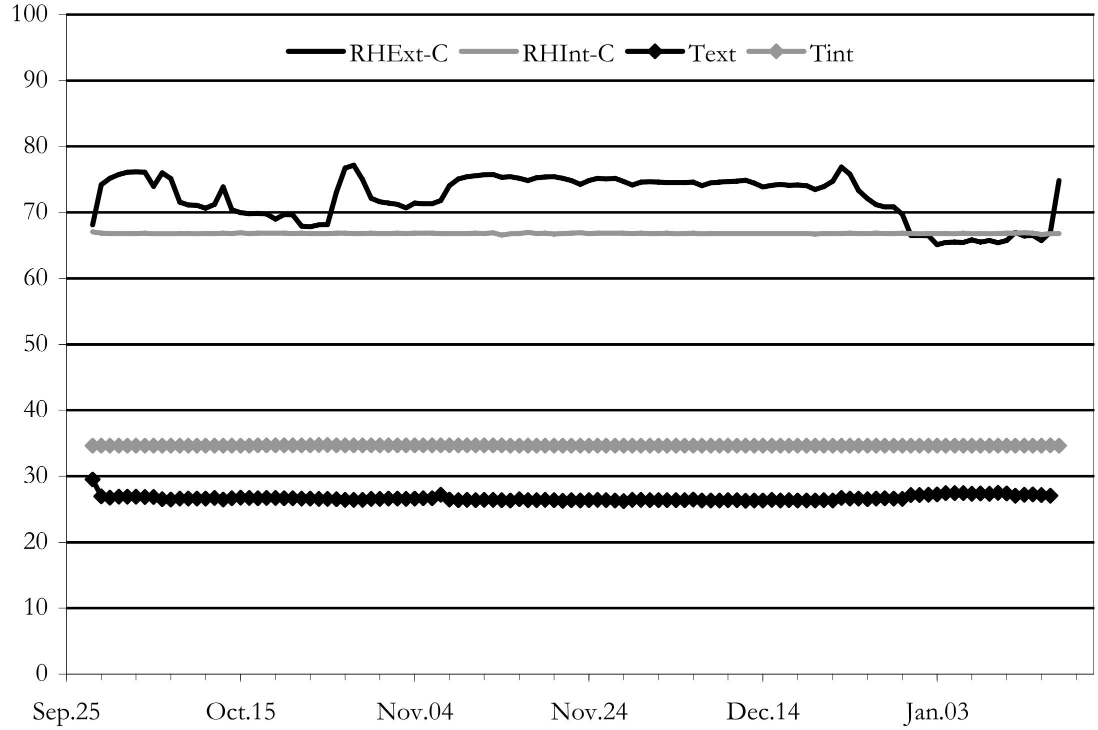

Figure 7-21: Temperature (°C) and Relative Humidity (%RH) Conditions from the Climate Chamber in Test Number 3 (Daily Average)

RHExt-C	Relative Humidity Climate Side
RHInt-C	Relative Humidity Interior Side
Text	Temperature Climate Side
Tint	Temperature Interior Side

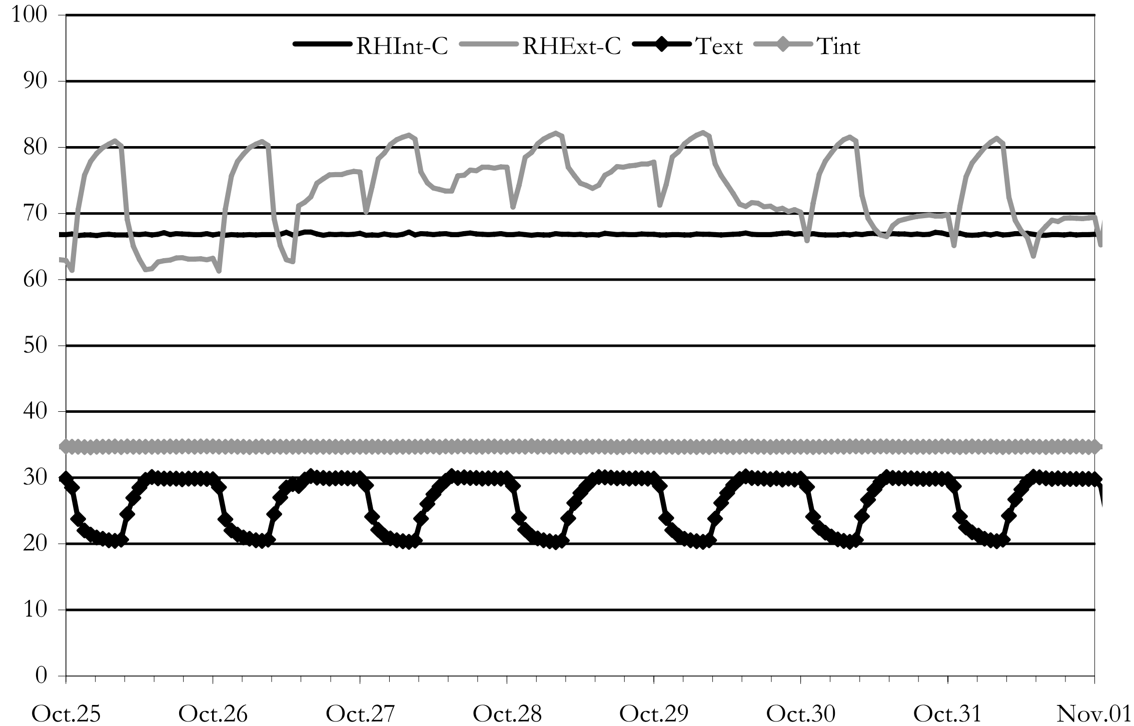

Figure 7-22: A Weekly Cycle of the Temperature (°C) and Relative Humidity (%RH) Conditions from the Climate Chamber in Test Number 3

RHExt-C	Relative Humidity Climate Side
RHInt-C	Relative Humidity Interior Side
Text	Temperature Climate Side
Tint	Temperature Interior Side

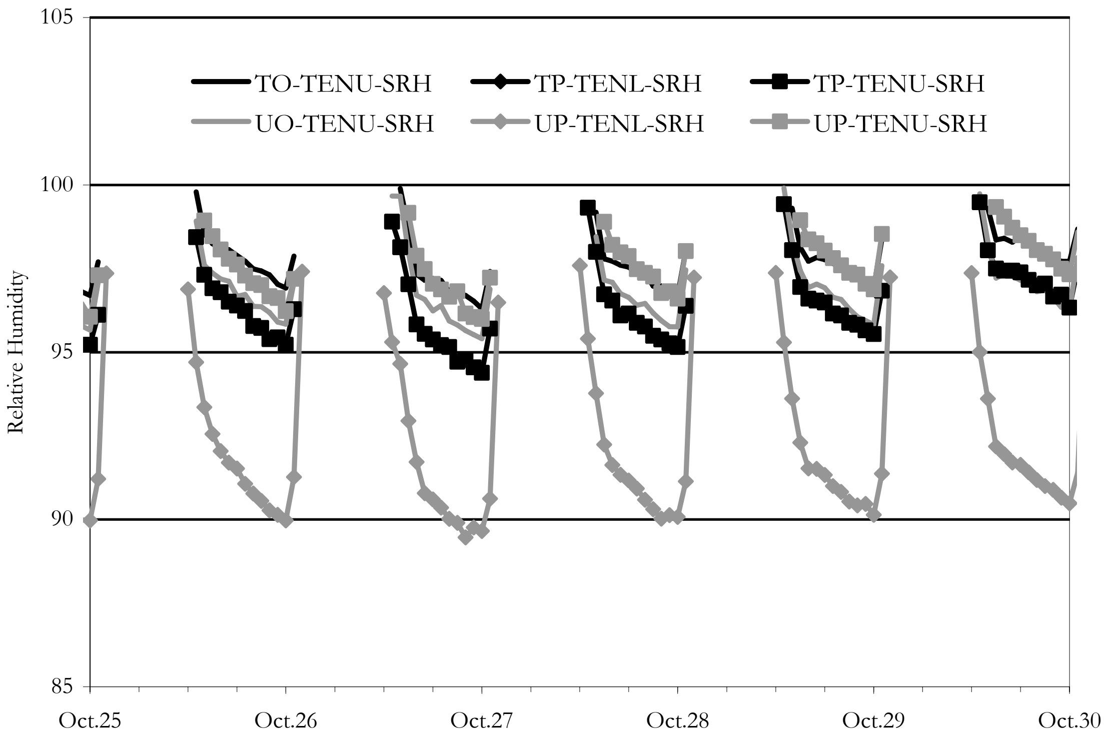

Figure 7-23: A Weekly Cycle of the Relative Humidity at Back of Sheathing in Test Number 3

TO-TENU-SRH	Treated OSB in Upper Quadrant
TP-TENL-SRH	Treated Plywood in Lower Quadrant
TP-TENU-SRH	Treated Plywood in Upper Quadrant
UO-TENU-SRH	Untreated OSB in Upper Quadrant
UP-TENL-SRH	Untreated Plywood in Lower Quadrant
UP-TENU-SRH	Untreated Plywood in Upper Quadrant

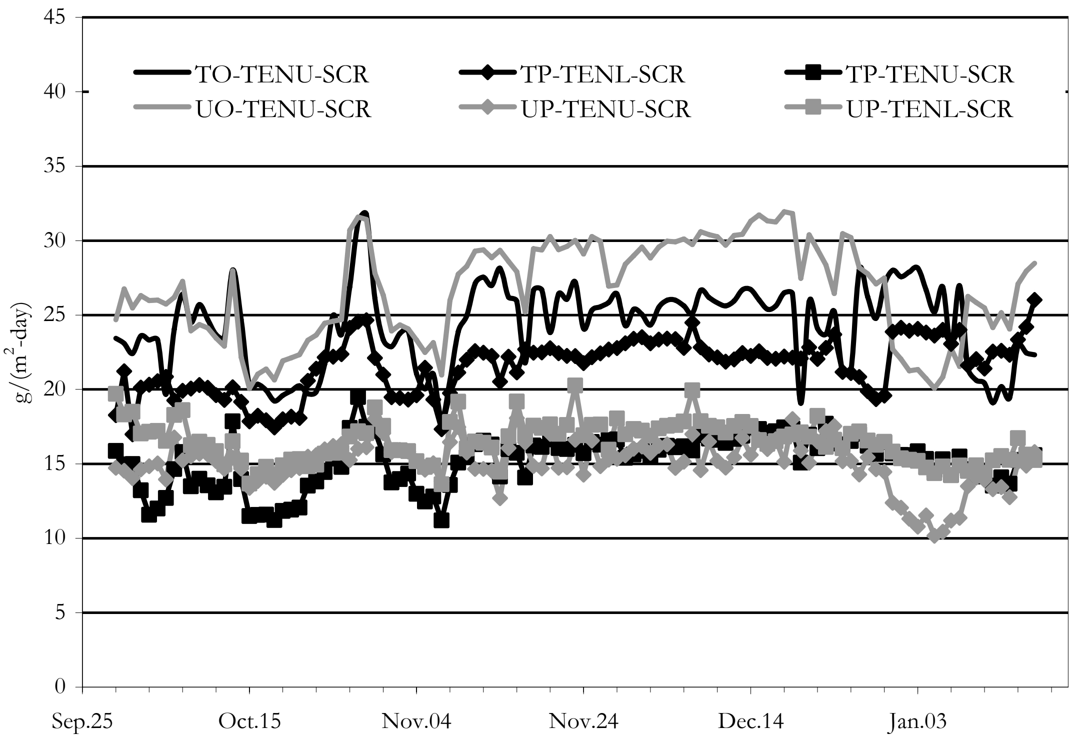

Figure 7-24: Condensation Rate on Back of Sheathing in Test Number 3 (Daily Average)

TO-TENU-SRH	Treated OSB in Upper Quadrant
TP-TENL-SRH	Treated Plywood in Lower Quadrant
TP-TENU-SRH	Treated Plywood in Upper Quadrant
UO-TENU-SRH	Untreated OSB in Upper Quadrant
UP-TENL-SRH	Untreated Plywood in Lower Quadrant
UP-TENU-SRH	Untreated Plywood in Upper Quadrant

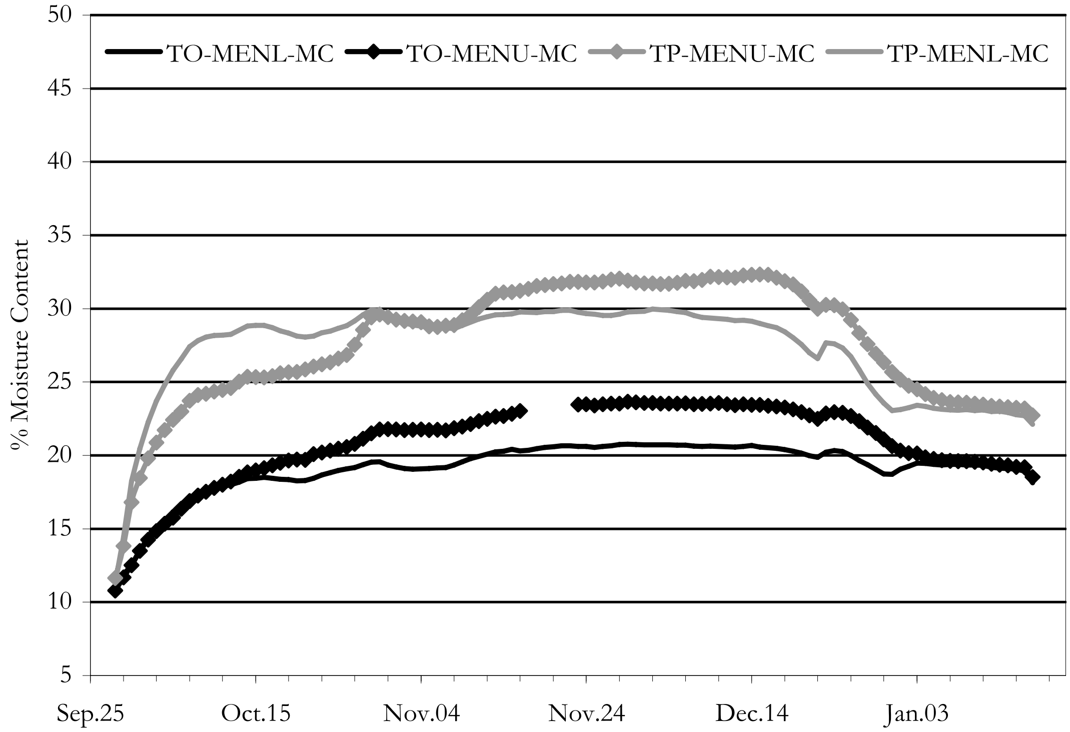

Figure 7-25: Moisture Content of Treated Sheathing in Test Number 3 (Daily Average)

TO-MENL-MC	Treated OSB in Lower Quadrant
TO-MENU-MC	Treated OSB in Upper Quadrant
TP-MENU-MC	Treated Plywood in Upper Quadrant
TP-MENL-MC	Treated Plywood in Lower Quadrant

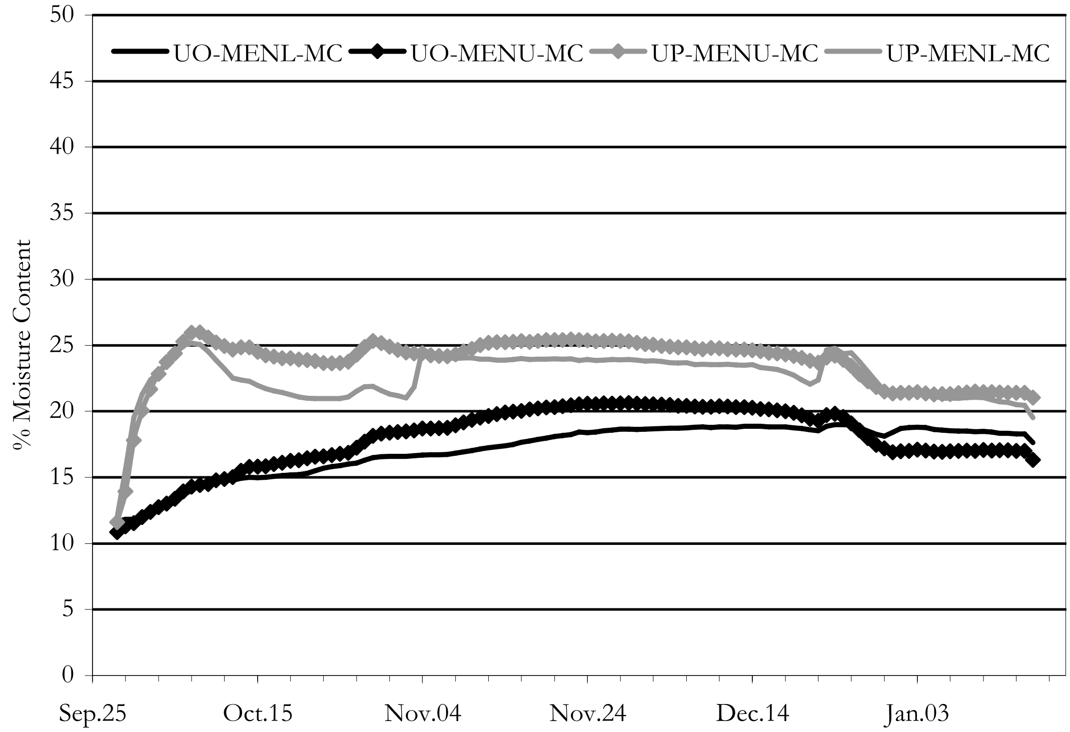

Figure 7-26: Moisture Content of Untreated Sheathing in Test Number 3 (Daily Average)

UO-MENL-MC	Untreated OSB in Lower Quadrant
UO-MENU-MC	Untreated OSB in Upper Quadrant
UP-MENU-MC	Untreated Plywood in Upper Quadrant
UP-MENL-MC	Untreated Plywood in Lower Quadrant

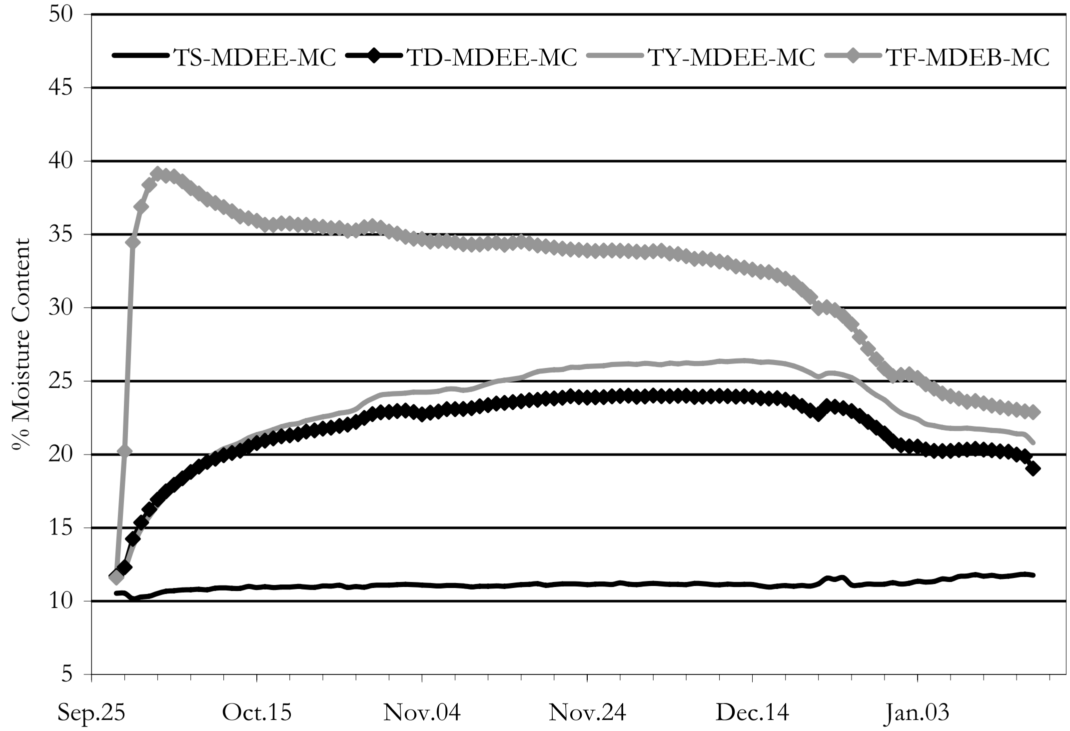

Figure 7-27: Moisture Content of Treated Dimensional Lumber in Test Number 3 (Daily Average)

TS-MDEE-MC	Treated Spruce Pine Fir
TD-MDEE-MC	Treated Douglas Fir
TY-MDEE-MC	Treated Southern Yellow Pine
TF-MDEB-MC	Bottom Plate

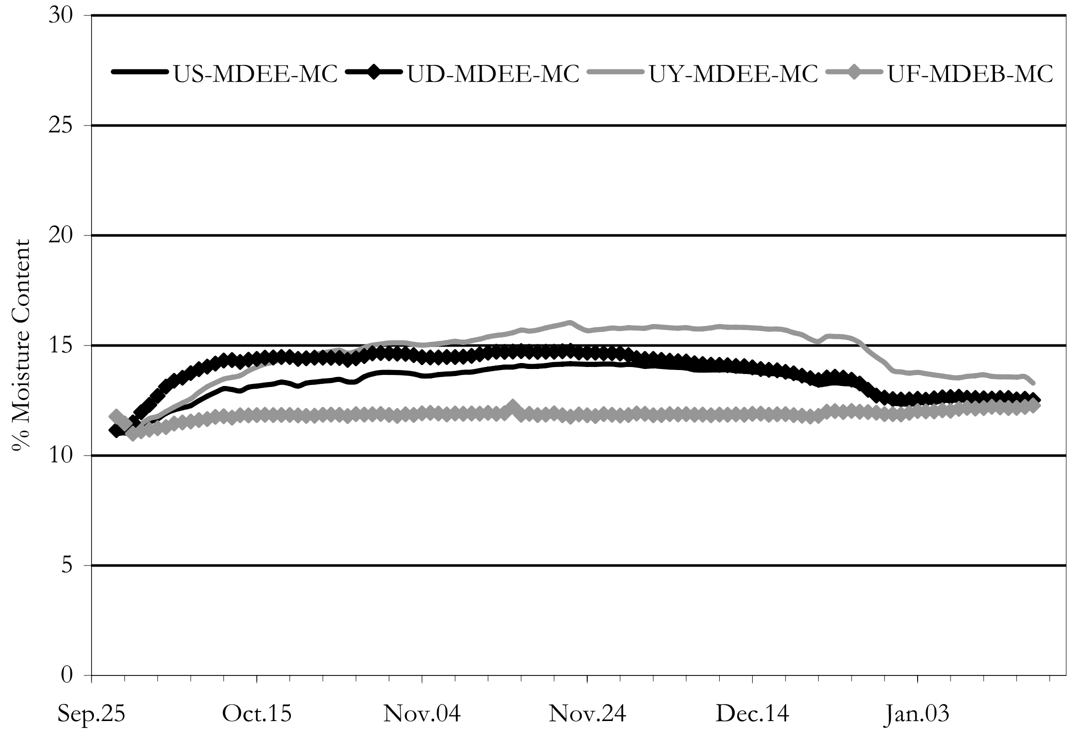

Figure 7-28: Moisture Content of Untreated Dimensional Lumber in Test Number 3 (Daily Average)

US-MDEE-MC	Untreated Spruce Pine Fir
UD-MDEE-MC	Untreated Douglas Fir
UY-MDEE-MC	Untreated Southern Yellow Pine
UF-MDEB-MC	Bottom Plate

8 Discussion

8.1 Visual Inspection

As previously mentioned during each of the three tests visual inspections of each of the eight test ports were performed using the mould index developed by Viitanen (Table 3-1). Refer to Appendix D for a visual correlation between the mould index and images of mould growth. Figure 8-2 thru Figure 8-13 plot the mould index and moisture content of each test port versus the time which is measured in weeks from the start of each test. Figure 8-1 is the legend for Figure 8-2 thru Figure 8-13.

Mould Index in Upper Quadrant

Moisture Content in Upper Quadrant

Mould Index in Lower Quadrant

Moisture Content in Lower Quadrant

Figure 8-1: Legend for Figure 8-2 thru Figure 8-13

8.1.1 Test Number 1

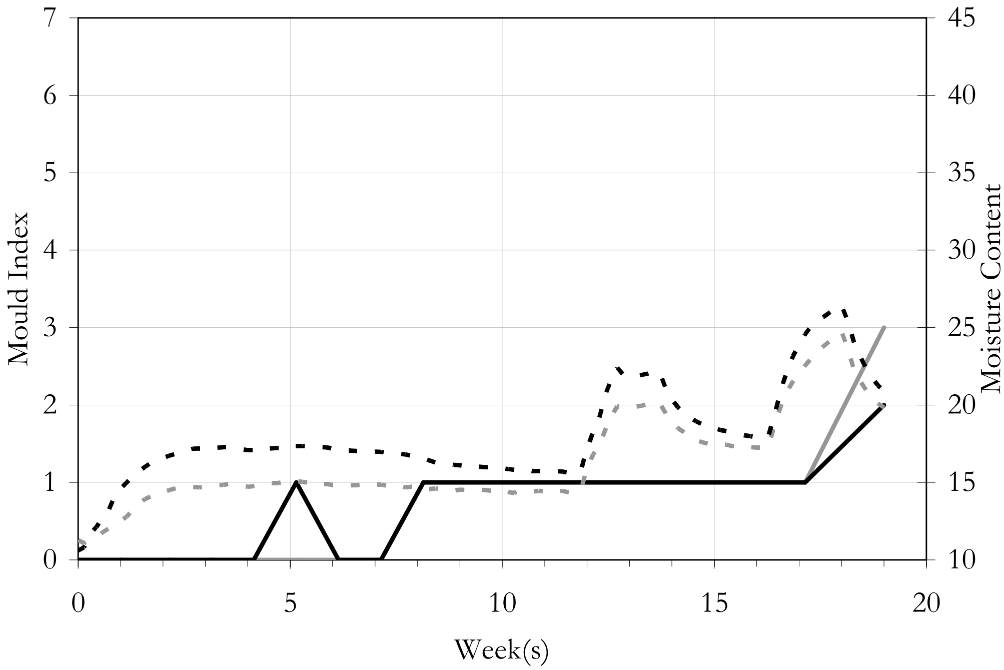

Figure 8-2: Moisture Content and Mould Index for Treated OSB in Test Number 1

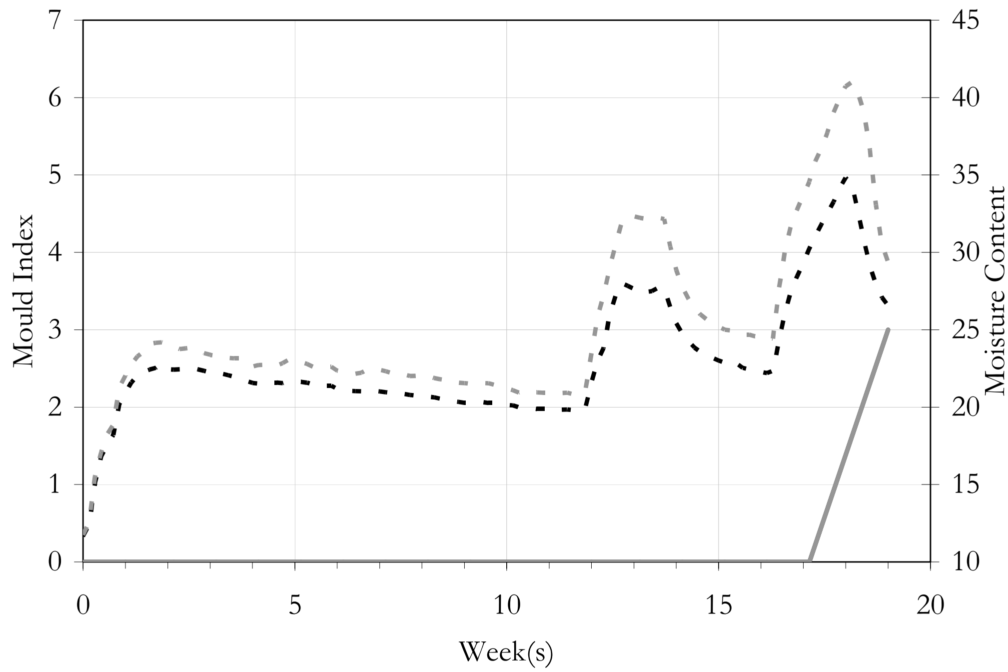

Figure 8-3: Moisture Content and Mould Index for Treated Plywood in Test Number 1

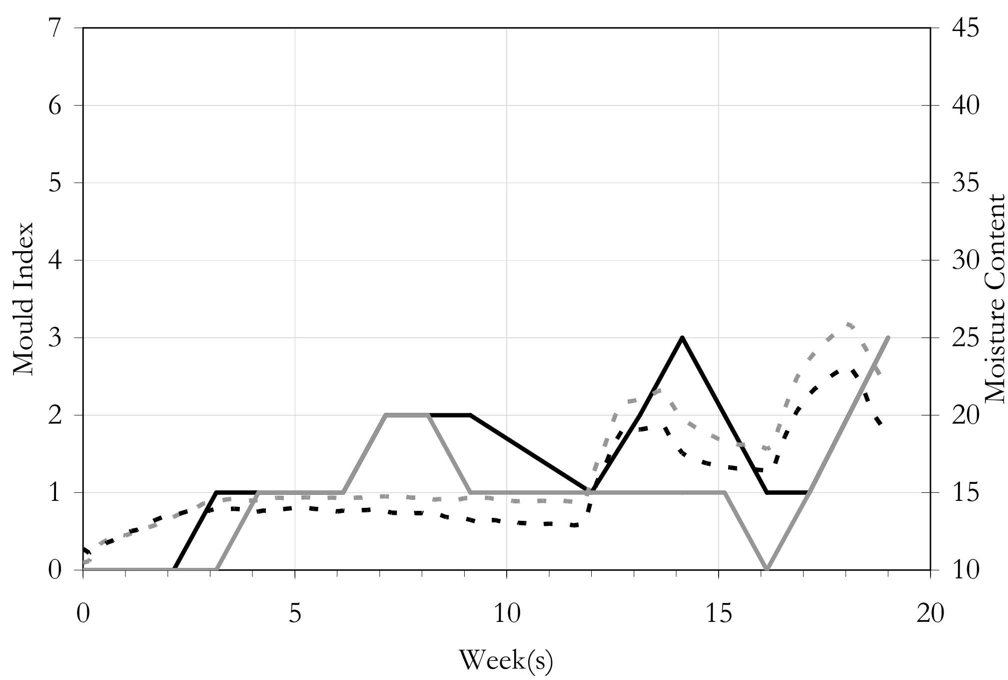

Figure 8-4: Moisture Content and Mould Index for Untreated OSB in Test Number 1

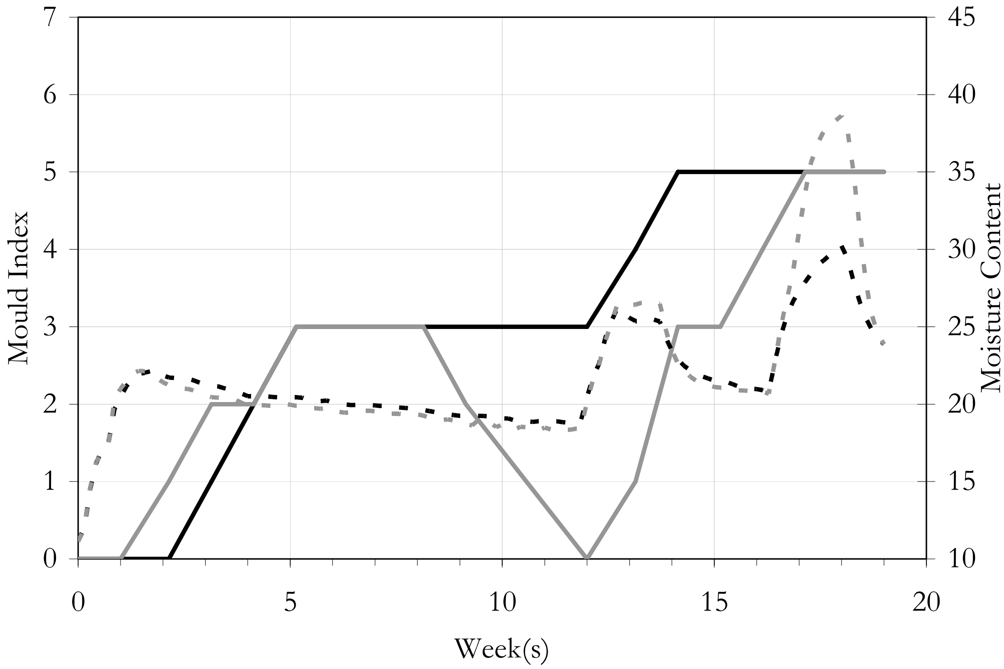

Figure 8-5: Moisture Content and Mould Index for Untreated Plywood in Test Number 1

8.1.2 Test Number 2

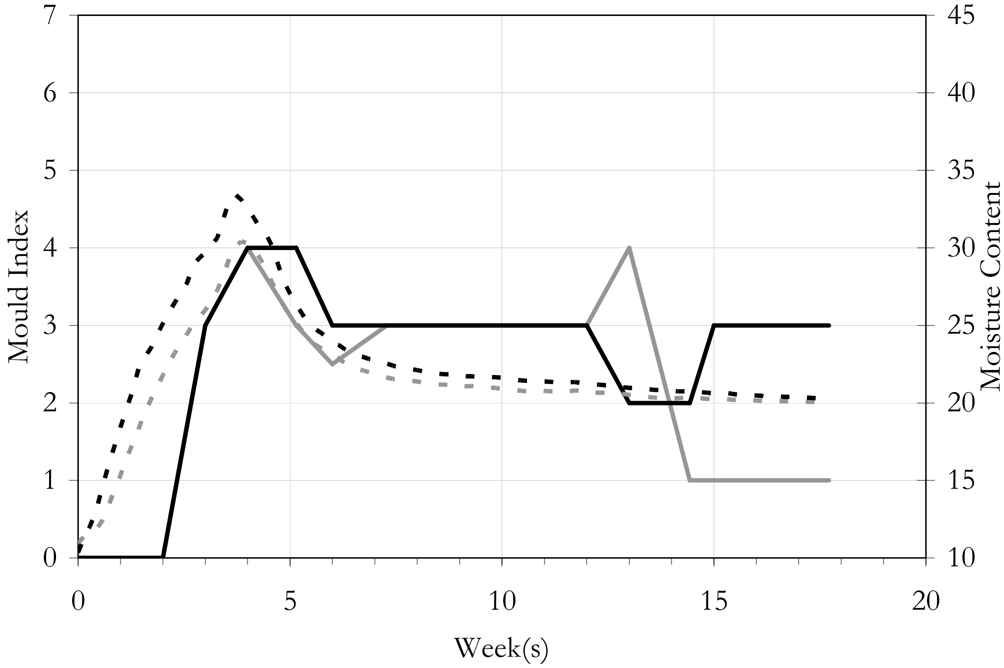

Figure 8-6: Moisture Content and Mould Index for Treated OSB in Test Number 2

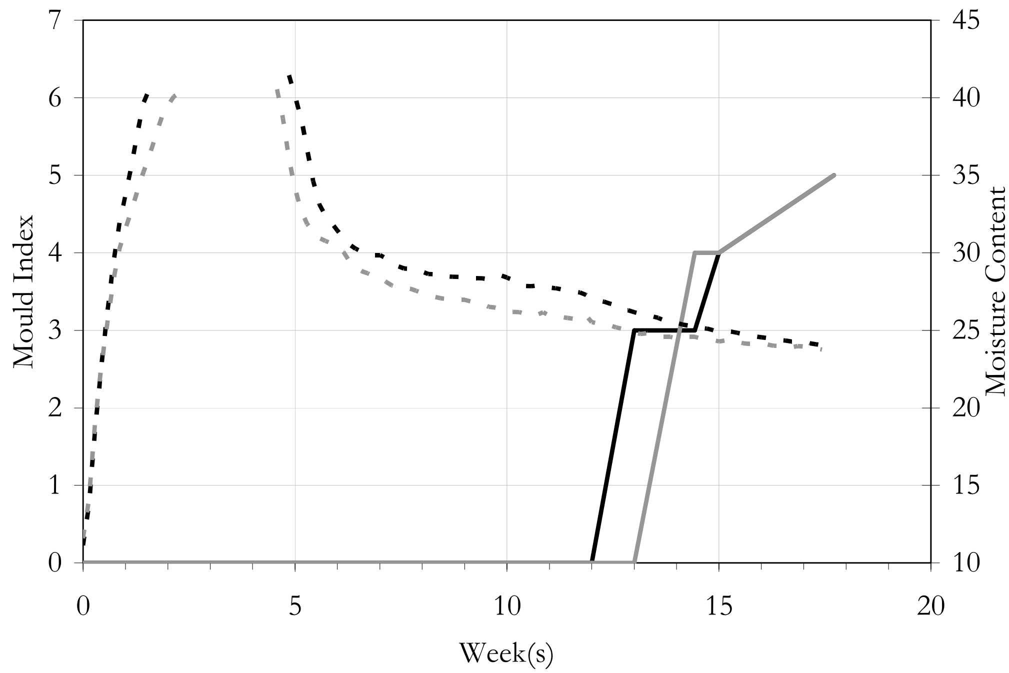

Figure 8-7: Moisture Content and Mould Index for Treated Plywood in Test Number 2

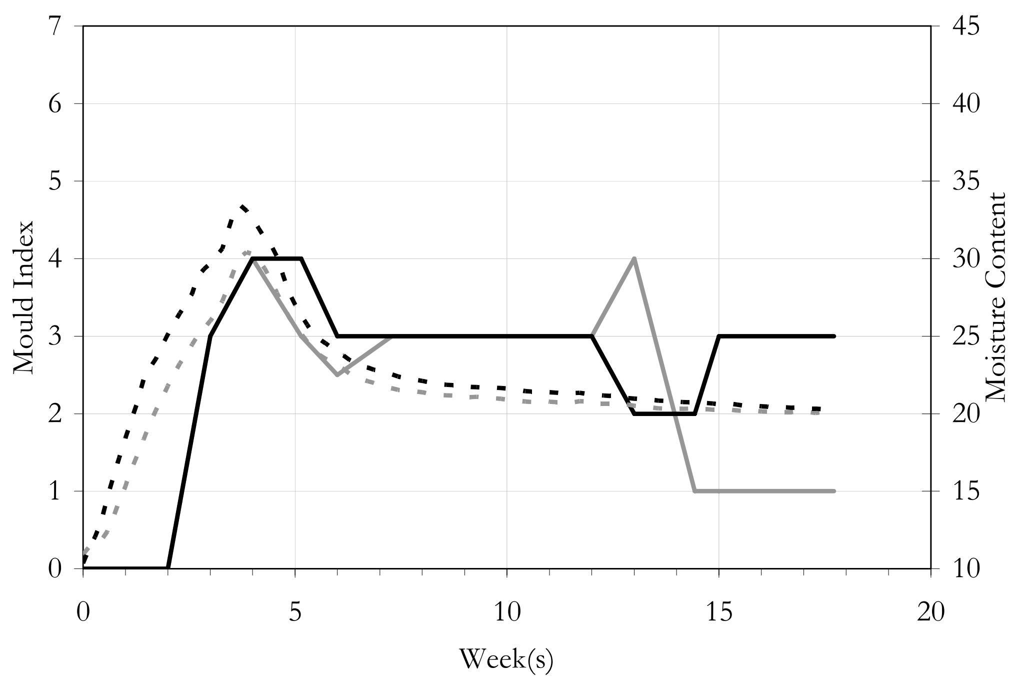

Figure 8-8: Moisture Content and Mould Index for Untreated OSB in Test Number 2

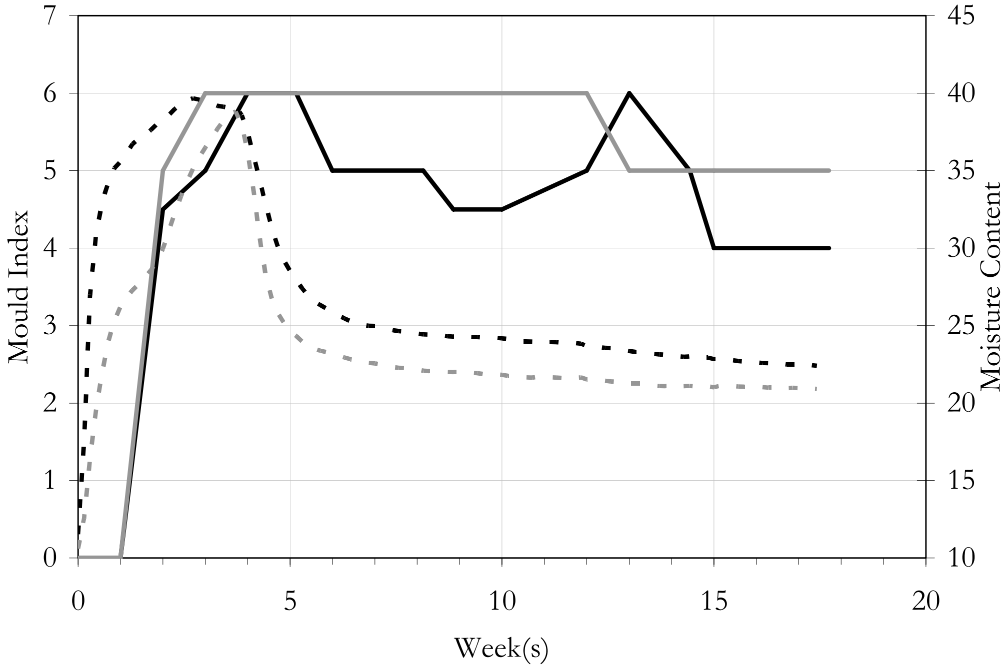

Figure 8-9: Moisture Content and Mould Index for Untreated Plywood in Test Number 2

8.1.3 Test Number 3

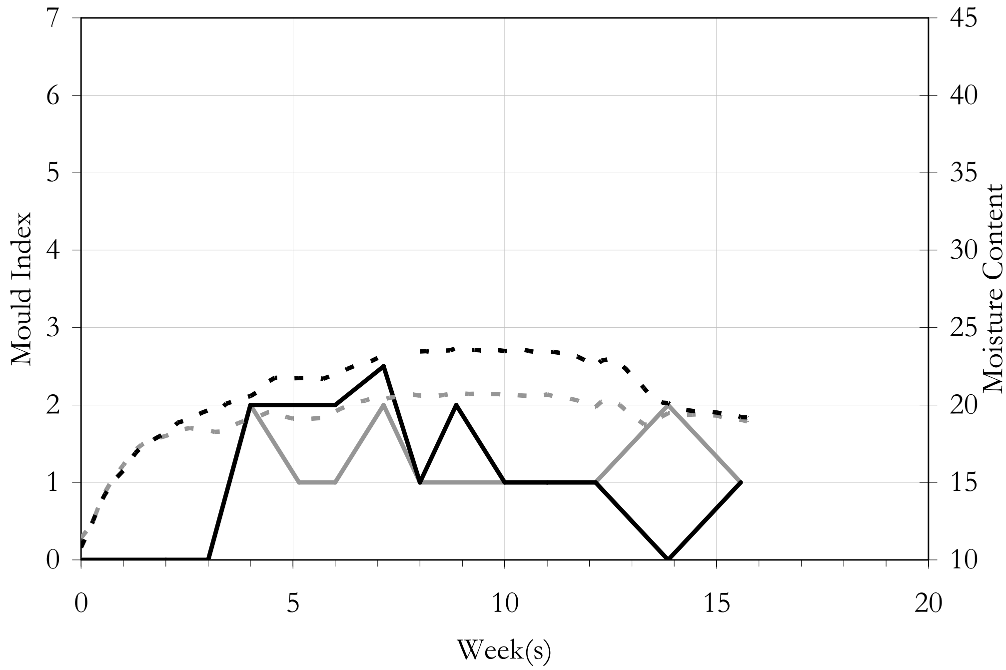

Figure 8-10: Moisture Content and Mould Index for Treated OSB in Test Number 3

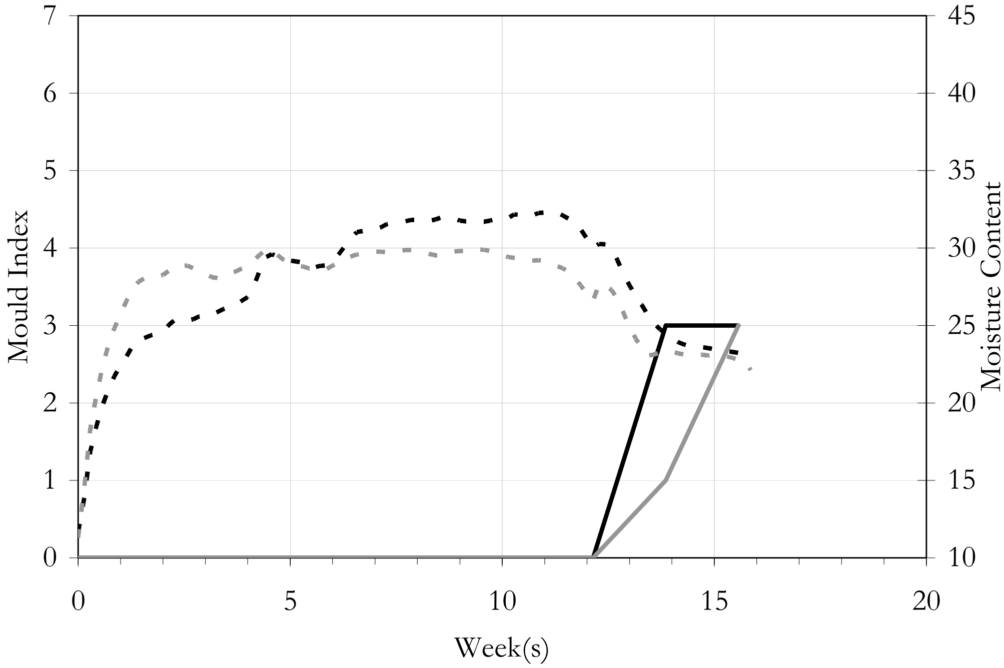

Figure 8-11: Moisture Content and Mould Index for Treated Plywood in Test Number 3

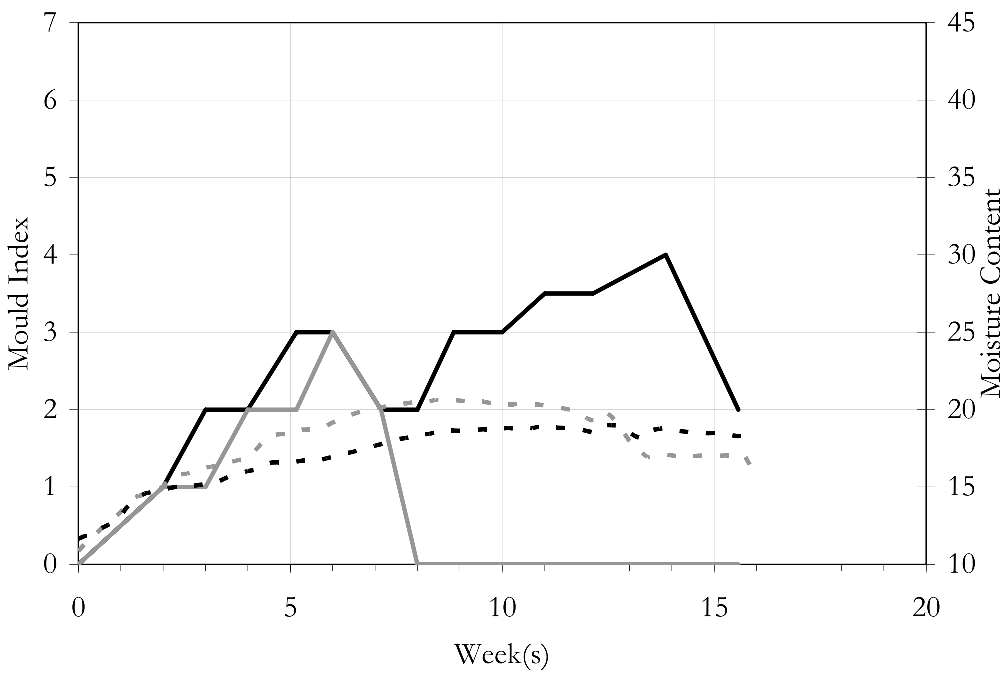

Figure 8-12: Moisture Content and Mould Index for Untreated OSB in Test Number 3

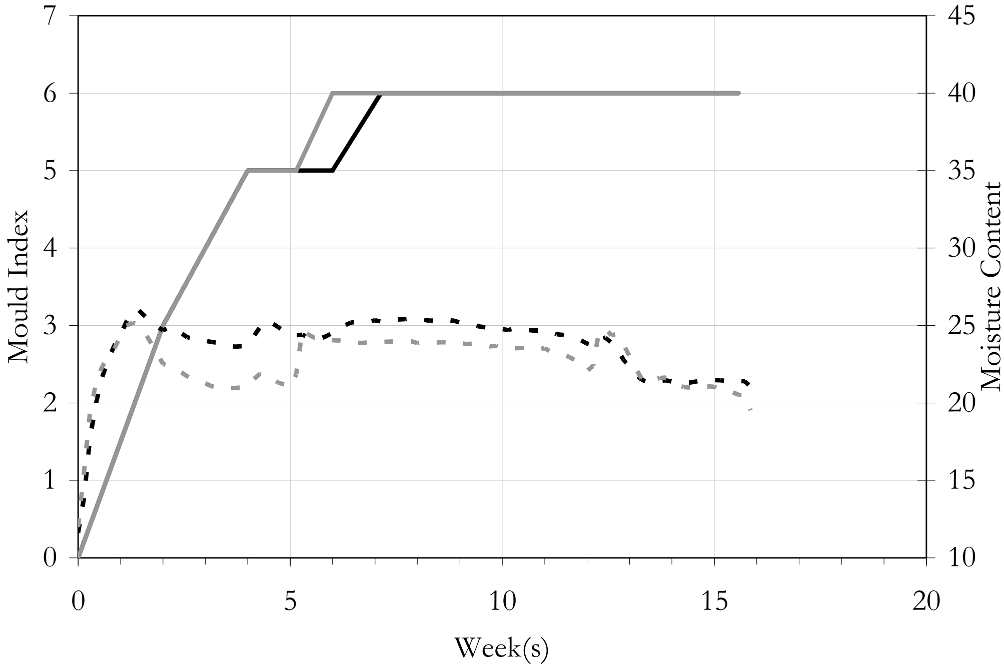

Figure 8-13: Moisture Content and Mould Index for Untreated Plywood in Test Number 3

8.2 Additional Visual Observations

Other than monitoring the growth of mould some other visual observations were made during the course of the experiment.

During all three tests small beetle like bugs were observed on the sheathing. These bugs were not observed at the start of the test but were observed after mould growth had been observed. The occurrence of bugs seemed to correlate with the growth of mould. Lab technicians from the Biology Department of the University of Waterloo confirmed that the bugs may have been living off of the mould, however, identification of the bug species would be difficult.

During the visual inspection which correlated to periods in which condensation conditions existed small droplets of liquid water were observed on the OSB sheathing, where as the plywood was damp to the touch. This may be due to the rate of water absorption being exceeded in the OSB or due to the OSB reaching its saturate moisture content. As the measure moisture content was much less than saturation, the former explanation is much more likely. The use of waxes in OSB reduces the moisture uptake.

8.3 Dimensional Lumber

The focus of this study was on the sheathing and its mould growth resistance. However, both the sheathing and the dimensional lumber were examined. No mould growth was observed on the dimensional lumber, even around the edges of the test ports where the sheathing was in contact with framing. There are several theories why mould growth did not occur on the framing. One of those theories is the safe storage capacity of the framing is higher than that of the sheathing therefore the moisture content of the framing did not rise high enough to result in moisture conditions which would support mould growth. The second theory is the studs were warmer due to thermal bridging which resulted in a lower surrounding relative humidity and prevented condensation from occurring. Finally, solid wood could simply be more resistant to mould growth than OSB and plywood.

8.4 Treated versus Untreated Sheathing

The moisture content of the treated OSB and untreated OSB were very similar, however, when examining the relationship between untreated and treated plywood the moisture content of the treated plywood was higher. This may be a result of the plywood being treated differently than that of the OSB. Both of which may influence the electrical resistance of the wood.

Again the OSB and plywood must be discussed separately when examining the difference in mould resistance between the untreated and treated sheathing. The treated and untreated OSB performed fairly similarly with a tendency for the treated OSB to perform better than the untreated OSB at resisting mould growth. When examining the mould resistance between treated and untreated plywood it was clear the treated plywood had a much higher mould resistance than that of its untreated counter part. From these results it is clear the treated plywood is an effective treatment, however, either the treatment used for the OSB is not the effective or it is recommended to use a higher concentration of treatment in the OSB.

A comparison of Figure 8-7 and Figure 8-9 (Test Number 2) and Figure 8-11 and Figure 8-13 (Test Number 3) suggests that the Borate treatment of the plywood increased the time to germination significantly. However, once mould growth was initiated, the rate of mould growth is similar to that of the untreated sheathing. There is not sufficient evidence for this to be a firm conclusion, and further study is recommended.

8.5 Oriented Strandboard versus Plywood

When discussing the difference in mould resistance between untreated and treated sheathing it was also necessary to discuss the OSB and plywood separately, moreover, when discussing the difference between OSB and plywood it is necessary to examine the treated and untreated sheathing separately. Previously it was hypothesized there is a difference between the treatment used in plywood and the treatment used in OSB, therefore, when discussing the differences between the mould growth resistance of the OSB and plywood, only the untreated samples will be discussed to remove the affect that the differences in treatments have on the samples.

Comparing the moisture content of OSB and plywood based on the resistance of the wood poses additional problems because the material properties of OSB and plywood are very different. For example OSB is denser than plywood and is less permeable and takes longer to reach moisture equilibrium. The core gaps in the core veneers of the plywood lead to large increase in resistance depending on the orientation of the pins relative to the grain in the core. The Lathe checks in plywood increase the likelihood that resistance will be higher across the grain and will more easily allow water to move around once past the face veneer. During the OSB manufacturing process the cell walls are crushed or damaged which inhibits the flow of water through the OSB. Furthermore the density of OSB is higher which also slows the movement of moisture throughout the OSB.

The above differences in OSB and plywood explain the difference in lag of moisture content when comparing OSB and plywood. These differences also explain the difference in the observed moisture contents which were based upon the wood resistance readings. Currently reliable correction factors do not exist for OSB or plywood. Moreover, for the conditions which the sheathing was exposed to during the tests, a reliable correction factors may not be possible because fibre saturation has been exceeded and once this is done according to personal communication with Donald Onysko reliable correct factors are not possible and only trends can be examined.

Despite these differences, the relative humidity behind the sheathing, the conditions which the OSB and plywood sheathing are exposed to are effectively identical. Furthermore, according to personal communication with Donald Onysko the measured difference between OSB and plywood moisture content can be explained by the above difference. Therefore, the OSB and plywood are exposed to the same conditions. Assuming the OSB and plywood sheathings were exposed to the same conditions it is obvious that plywood is capable of supporting a much higher growth rate than that of OSB. However, in this study the permeance of the plywood was altered by the addition of additional layers of Tyvek™. Additional tests should be run with different test wall assemblies to verify the conclusion that plywood is capable of supporting a higher growth rate than that of OSB.

8.6 Upper Quadrant versus Lower Quadrant

During the three tests the moisture content of the upper quadrants were higher than that of similar lower quadrants, however, some exceptions to this trend can be found. Additionally, the mould growth rate was similar between the upper and lower quadrants when examining similar sheathing products. From these results it can be shown that no excessive moisture was condensing on the sheathing and running down the sheathing. If run down was occurring higher moisture content readings would have been observed on the lower quadrants when compared with the upper quadrants.

8.7 Mathematical and Computer Modeling

8.7.1 Viitanen Mould Growth Model

All three of the climate chamber tests were modeled using Viitanen's mould growth model. The predicted amount of mould growth on the sheathing is illustrated in Figure 8-14 for each of the tests. For the analysis the following assumption at the back of the sheathing were made: for test number 1 26°C and 95% RH, for test number 2 26°C and 95% RH, and for test number 3 20ºC and 100% RH for 8 hours and 30ºC and 80% RH for 16 hours each 24 hour period.

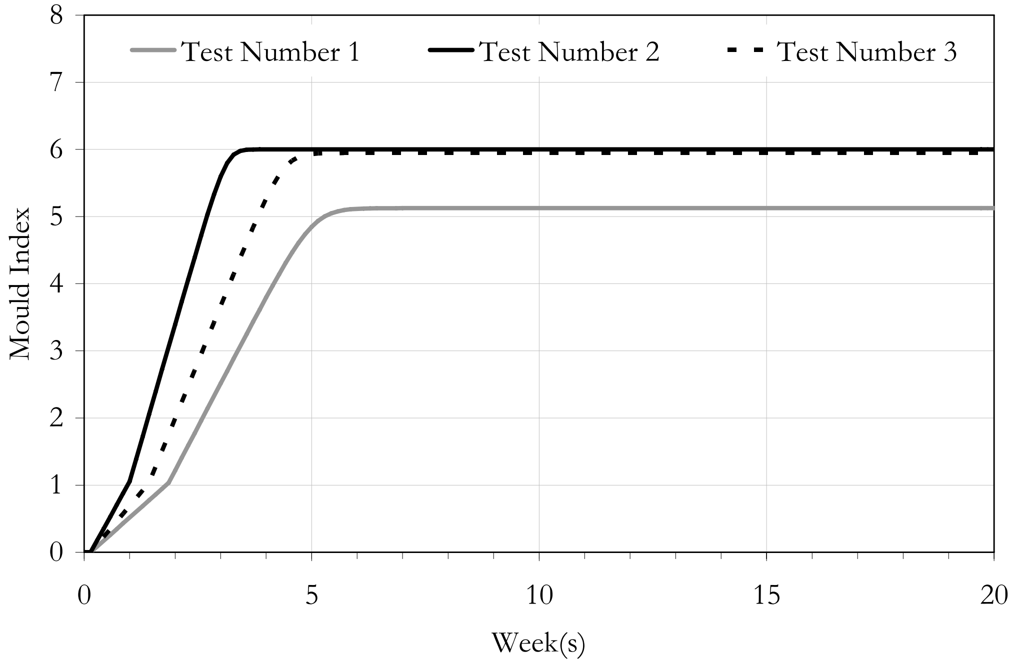

Figure 8-14: Calculated Mould Growth Rate Using Viitanen's Model

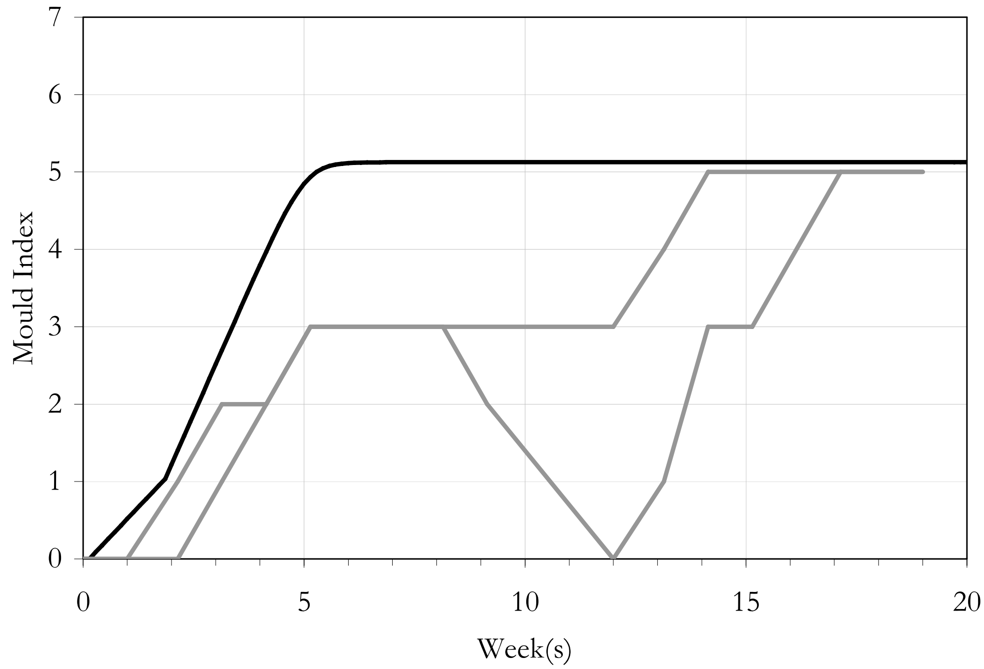

Figure 8-15: Calculated Mould Growth Rate (Black Line) versus Observed Mould Growth on Untreated Plywood (Grey Line) for Test Number 1

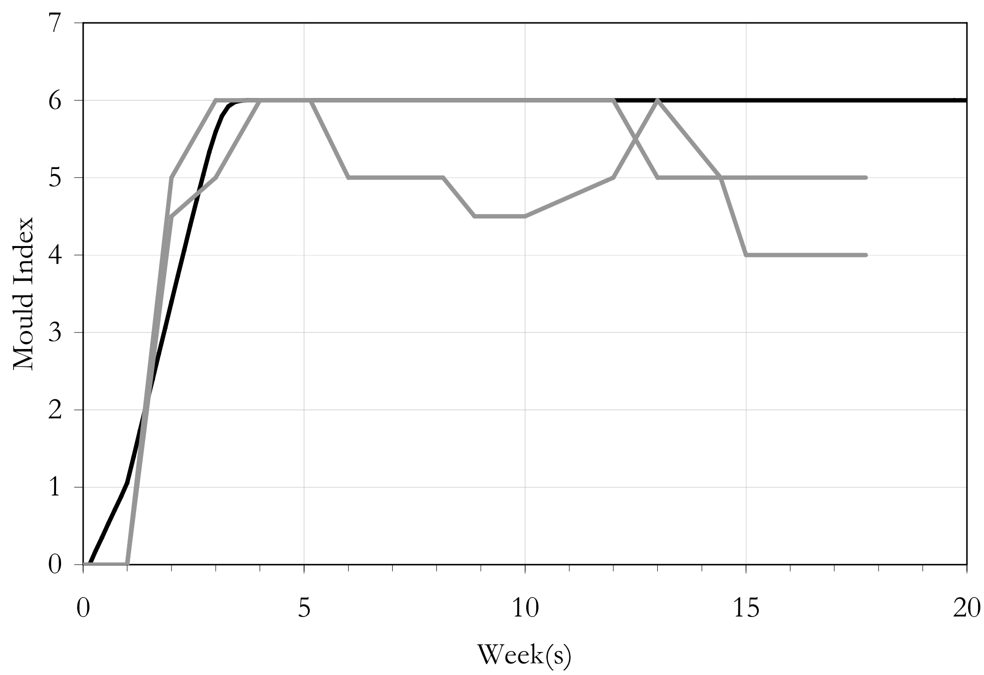

Figure 8-16: Calculated Mould Growth Rate (Black Line) versus Observed Mould Growth on Untreated Plywood (Grey Line) for Test Number 2

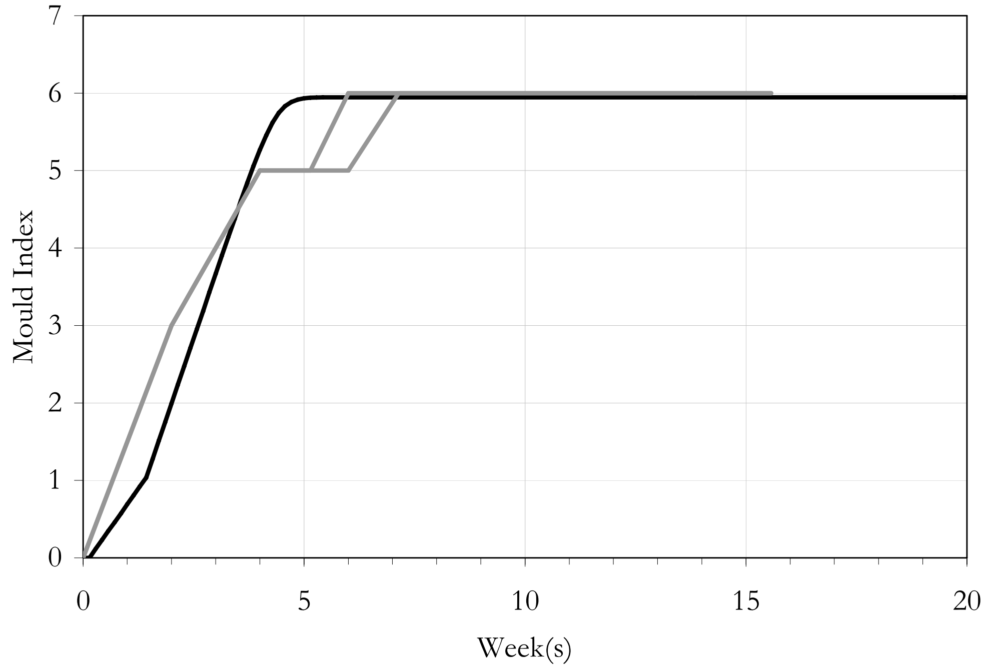

Figure 8-17: Calculated Mould Growth Rate (Black Line) versus Observed Mould Growth on Untreated Plywood (Grey Line) for Test Number 3

Viitanen's mould growth model predicted much faster growth rates than what was observed. When comparing the model to the observed results of all three tests the model most closely matched the mould growth observed on the untreated plywood sheathing. For the untreated plywood case, the model predicts the maximum mould index closely with the observed growth rate except for test number 1. The reason for the discrepancy with test number 1 may be a result of the model assuming constant conditions where as in reality conditions varied over the length of the test. However, Viitanen mould growth model does not predict die off, a reduction in the amount of observed mould, which was observed in all three tests. Based on the results of the analysis it can be concluded Viitanen's model is accurate, however, it is conservative predicting mould growth for a solid wood substrate.

8.7.2 WUFI Model

A hygrothermal computer modeling program was used to create a model of the wall assembly to further compare the conditions observed within the wall assembly, additionally a mould growth model was implemented to further verity the mould growth results of the study.

To perform the hygrothermal analysis a dynamic 1-dimensional tool "WUFI 4.1" was employed. WUFI (Kunzel 1997) is one of the most advanced commercially available hygrothermal software packages. WUFI allows for the hourly calculation of heat and moisture flow through an enclosure given the influences of solar, temperature, wind, rain and humidity. The accuracy of WUFI has been validated through many full-scale field studies on enclosure (Straube 2003). WUFI includes hourly climate data for many cities and a wide range of material properties.

To model mould growth an external program called "WUFIBIO" (IBP 2006) interfaces with WUFI 4 predicting the growth rate, critical water content, and water content of mould spores. For this simulation WUFIBIO 2 was used. Using the results from the WUFIBIO analysis it is possible to compare mould germination times and conditions that produce the fastest growth rates.

The materials properties used in the analysis were all found within the WUFI materials database, expect for the Tyvek™ which properties were inputted manually. Additionally the sheathing was modeled as two layers one 10 mm and one 1 mm piece. This makes it possible to determine the moisture content at the critical surface. The model was constructed to match the wall assembly tested and both types of sheathing were modeled, OSB and plywood. However, because the results from WUFIBIO for both the OSB and plywood sheathings were very similar and the mould growth model within WUFIBIO does not take into account the difference between the OSB and plywood, only the results for the OSB WUFI model are presented below. The exterior and interior climate conditions required by WUFI were taken directly from the measured relative humidity and temperature data record. This allowed for the most accurate simulation of the tests. For the WUFIBIO analysis the initial relative humidity conditions were assumed to 50% and a class 2 substrate was selected, which most closely matches the material properties of OSB and plywood. The results of the WUFI analysis are compared with the actual measured data and are presented in Figure 8-19 thru Figure 8-21. Figure 8-18 is the legend for Figure 8-19 thru Figure 8-21. The results of WUFIBIO are illustrated in Figure 8-22.

Figure 8-18: Legend for Figure 8-19 thru Figure 8-22

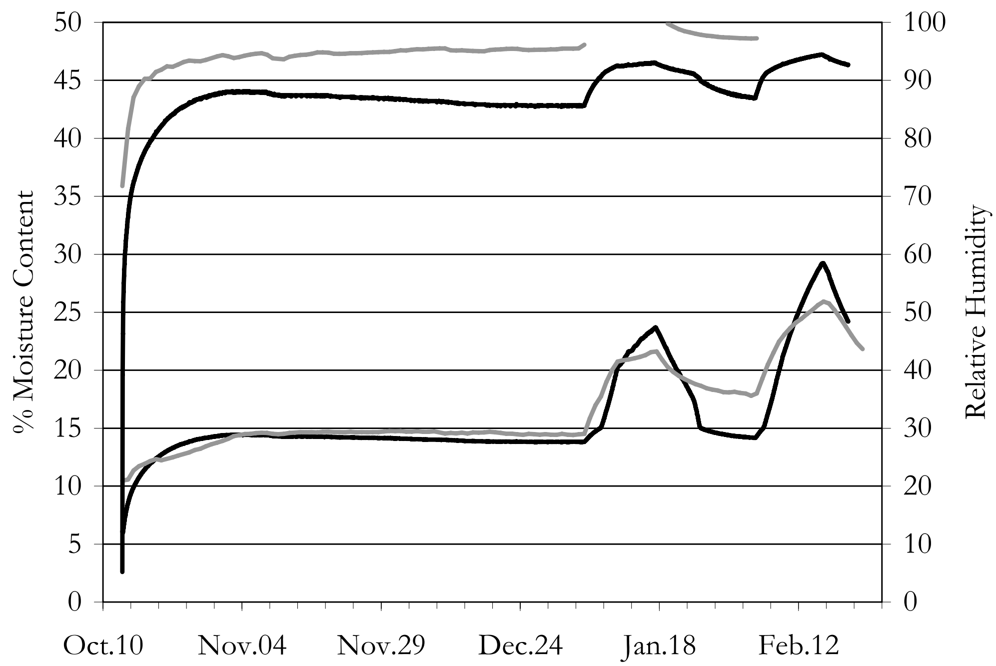

Figure 8-19: Predicted and Measured Moisture Content (Bottom Lines) and Relative Humidity (Top Lines) at the Back of the Sheathing for Test Number 1

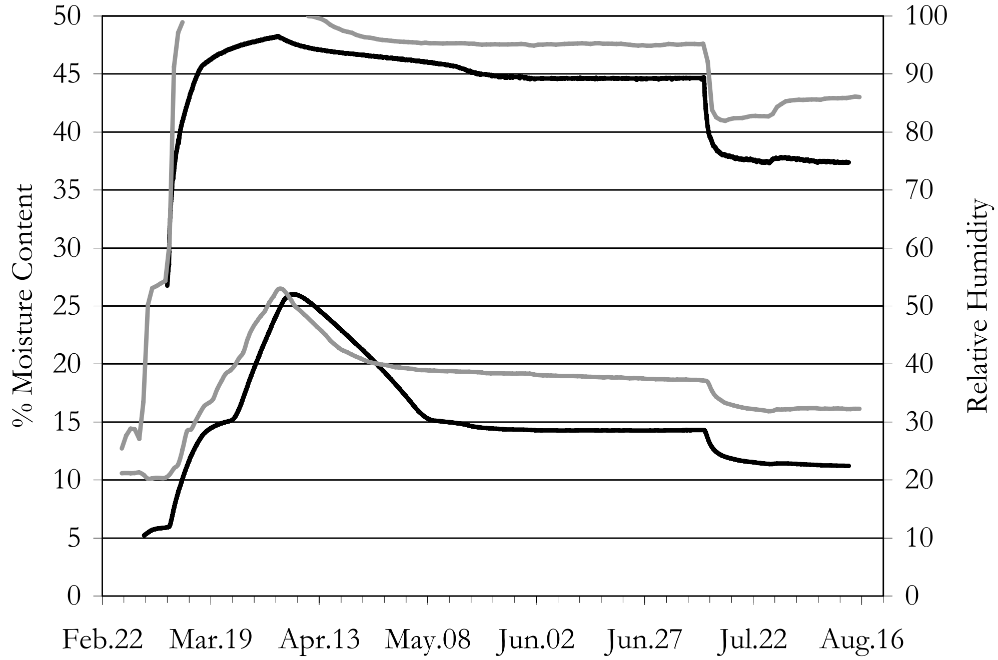

Figure 8-20: Predicted and Measured Moisture Content (Bottom Lines) and Relative Humidity (Top Lines) at the Back of the Sheathing for Test Number 2

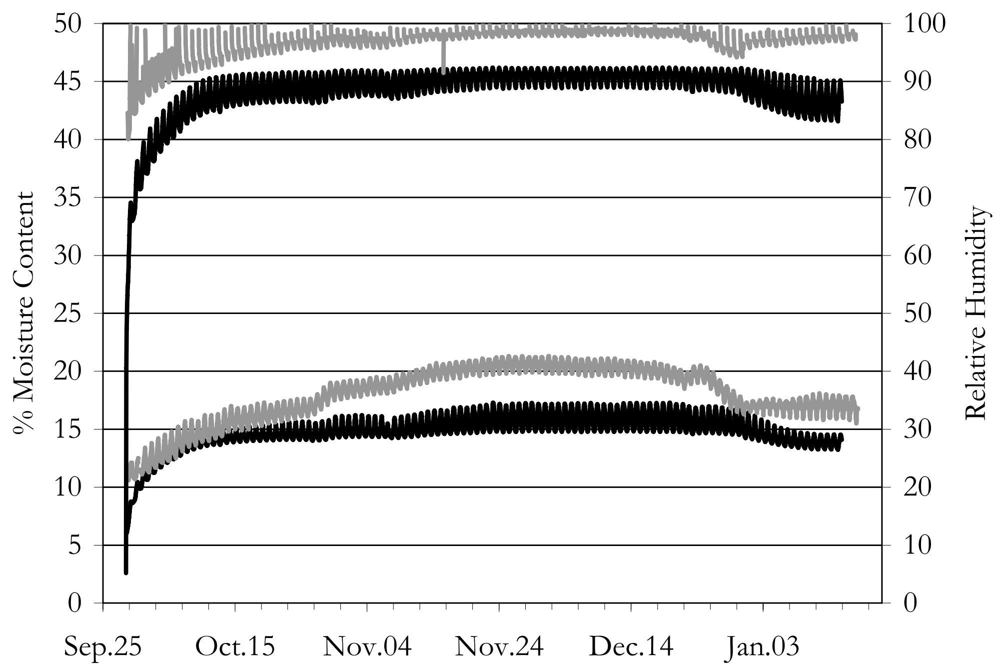

Figure 8-21: Predicted and Measured Moisture Content (Bottom Lines) and Relative Humidity (Top Lines) at the Back of the Sheathing for Test Number 3

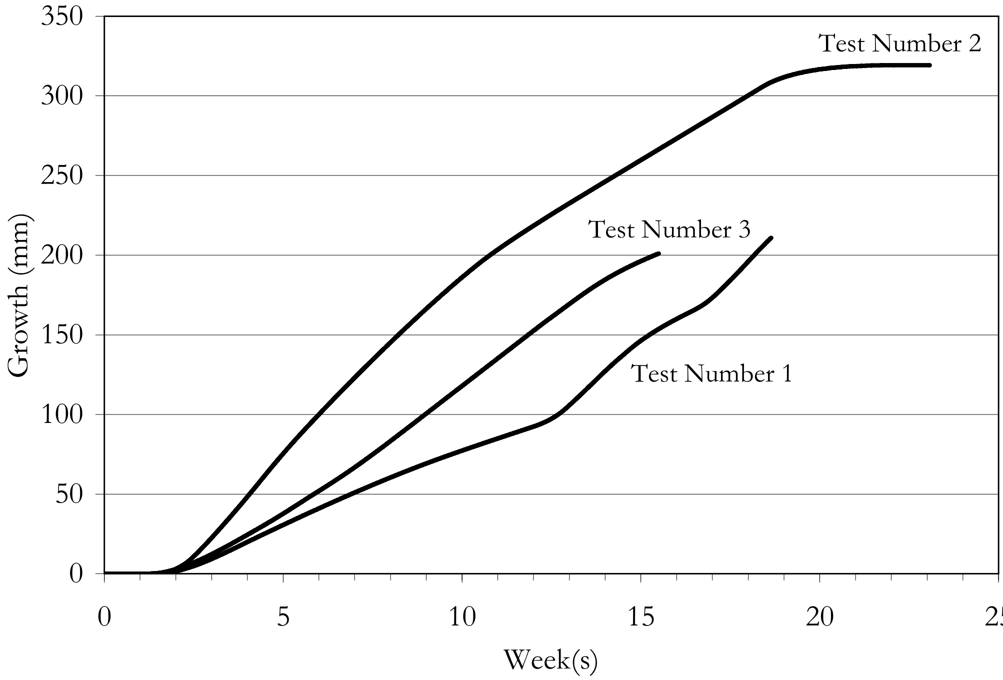

Figure 8-22: Predicted Mould Growth Rate Using WUFIBIO Model

The moisture content predicted by WUFI closely matches those observed in this study, and any difference between WUFI and the observed readings can be attributed to either errors in the location of the measurement, the use of uncorrected moisture content readings, or incorrect material property assumptions. The relative humidity predicted by WUFI on the back of the sheathing was low when compared with the results calculated from the measured conditions within the wall assembly. The difference in results between the WUFI model and the calculated conditions behind the sheathing may be attributed to the assumption that the vapour resistance of the Batt insulation was negligible. Given the large gradient over the entire assembly the previous assumption may have resulted in the calculation of an inflated relative humidity behind the sheathing. Additionally WUFI is better able to predict the varying materials properties within the wall assembly, storage capacity of those assemblies, and condensation conditions. Like Viitanen's model the WUFIBIO model most closely matches the results observed on the untreated plywood, closely predicting the time for the mould to germinate and become visible. WUFIBIO predicts this to occur at approximately

2 weeks after the start of the test for all three tests. However, the WUFIBIO model predicts complete coverage of the entire test panel 3 days after germination which does not correlate with the observed rate of mould growth.

8.8 Small Scale Mould Growth Study

Currently the popular belief in the industry is that mould growth will start if wood is exposed to a relative humidity of 80% or above. Therefore, in order to test this theory it was decided to place some small material samples in the climate side of the climate chamber during test number 2 as throughout this test the conditions remained constant at 80% and 25°C. The samples included treated and untreated samples of all three types of dimensional lumber, treated and untreated OSB and plywood, drywall, white bread, and pumpernickel bread.

All thirteen samples were placed in the climate side of the chamber on Thursday, November 25, 2004 and after one week the pumpernickel bread started to grow mould and after two weeks the white bread started to grow mould. After 2 months none of the other samples had shown any visible signs of mould growth. Figure 8-23 is an image of the mould growth on the pumpernickel bread after only 3 weeks. Although mould may begin growing under these conditions, these simple tests suggest that it will take more than 2 months.

Figure 8-23: Pumpernickel Bread After 3 Weeks

The evidence from this small study suggests that the commonly-quoted conditions for mould growth (80%RH at room temperature) are quite conservative. Furthermore, based on the testing of products considered highly susceptible to mould (such as bread) illustrate that mould occurs naturally within the environment and therefore inoculation is not necessary. In addition the different behaviour of the two samples of bread demonstrates that not all organic products are the same. Therefore, when comparing mould growth potential on different building products, care must be taken to precisely differentiate the products in question. It should be expected that different species of wood, wood grown in different locations, and wood products produced using different techniques will all have a different response to moisture and mould growth.

9 Conclusions

The objectives of this study were to determine the effect of temperature and relative humidity on mould growth of Borate treated and untreated wood and wood products.

The results of this study indicate that the relative humidity conditions needed for mould growth to occur in under two months on wood and wood products are higher than commonly believed (i.e., significantly greater than 80%RH). During the initial two months of the first test, little mould growth was observed on the untreated sheathing and little or no mould growth was observed on the treated sheathing. The second and third tests demonstrated that the presence of liquid water greatly accelerated the time to germination, the amount of mould growth, and the rate of mould growth.

To further illustrate the conservative value the industry assumes for the critical relative humidity for mould growth, tests were performed on smaller samples of wood, wood products, and foodstuffs maintained at a relative humidity of 80% and a temperature of 25°C. No mould growth was observed on the wood samples after 2 months.

Mould growth did not form on the solid wood framing during any of the tests, even under the worst conditions. Although the tests were only 16 to 19 weeks long, decay was not observed in the sheathing in any of the tests, even those which subjected the sheathing to moisture contents of well over 30%.

All three tests clearly showed that borate-treatment reduced the amount of mould growth; however, the concentration of borate-treatment, and the types of materials treated, does appear to impact the resistance to mould growth. As found by Li (Li 2005) higher levels of Borate may be needed in OSB products to increase mould resistance significantly.

There is some evidence to suggest that the Borate treatment of the plywood increased the time to germination significantly. However, once mould growth was initiated, the rate of mould growth was similar to that of the untreated plywood.

Two mathematical models to determine mould growth were examined: Viitanen and WUFIBIO (Sedlbauer). It was determined by comparing the measured results to the models results that Viitanen's model predicted the time to germination and rate of growth rate well for untreated plywood. The WUFIBIO model was only able to accuracy predicted the time to germination time but not the growth rate. However, both models err on the side of caution predicting mould growth on the most susceptible wood species in this study, untreated plywood. The WUFI model predicted the moisture content of the sheathing rather well.

10 Recommendations

Once the tests were completed and the results were analyzed it was obvious certain improvements to the experimental design and can be recommended.

In order to improve the accuracy of the measured moisture content and allow for the better comparison of the moisture contents within the different types of wood products the resistance readings used to calculate the moisture content needs to be calibrated depending on the type of wood product being analysed. Within this study the measured moisture contents were not corrected. Donald Onysko (2006) suggested the calibration of the resistance readings of wood above fibre saturation is not possible. However, a study should be performed to determine the calibration of moisture contents below the fibre saturation and provide information about how the resistance changes above fibre saturation. Furthermore, the effect borate treatment has on the resistance of wood needs to be understood, and correction factors need to also be developed for borate treated wood products. Previous work by Onysko has suggested that this may not be possible.

As electrical resistance readings require calibration correction curves which lose accuracy at high moisture contents, gravimetric measurements are recommended in future lab tests. Instead of determining the moisture content based on electrical resistance, the moisture content can determined based on the measurements of the mass of sheathing samples. A piece of the sheathing such as the tests ports, could be removed regularly in order to determine the mass. At the end of the experiment the sample would be dried out completely to give the dry weight. This would allow for the moisture content to be determined accurately without the need to calibrate the measurements based on wood species. Moreover, the moisture content based on the mass of the sample can be compared to the resistance readings of the wood. This would allow for a better understanding of how the resistance of the wood varies above and below fibre saturation for different wood products.

Finally, additional tests need to be performed for OSB with a higher concentration of borate treatment. This is because the sample provided to Building Engineering Group did not show a greatly improved resistance to mould growth. Along with additional OSB samples other wood treatments could be tested, along with different species of OSB and plywood in order to determine the effect they have on mould growth. Additional tests should be run with different test wall assemblies to verify the conclusion that plywood is capable of supporting a higher growth rate than that of OSB. Additional tests need to be performed to determine if the mould growth rate for treated wood once initiated is similar to the rate of mould growth for untreated wood. A range of different temperatures and relative humidities should also be tested to expand our understanding of their impact. Furthermore, a test specially developed to test the mould resistance of the framing with the wall assembly should be developed as this test did not effectively test the mould growth resistance of framing within the test wall assembly.

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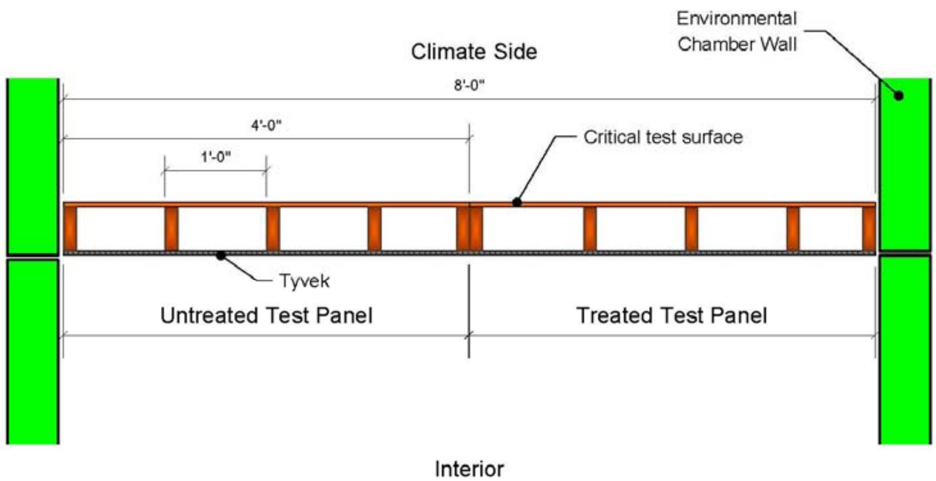
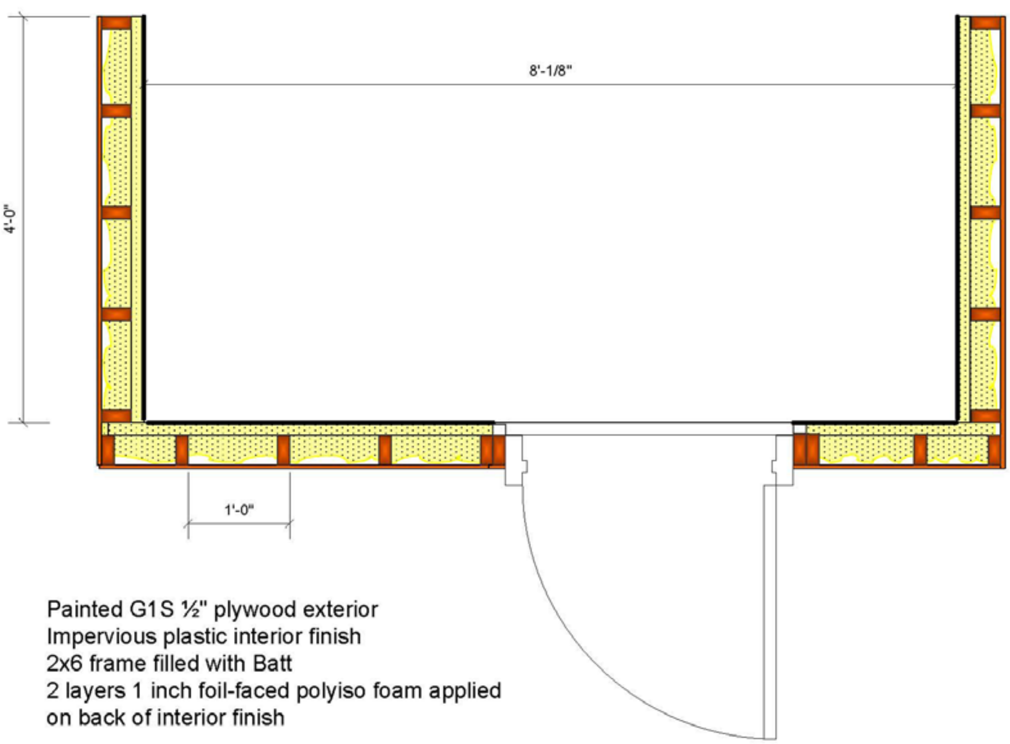
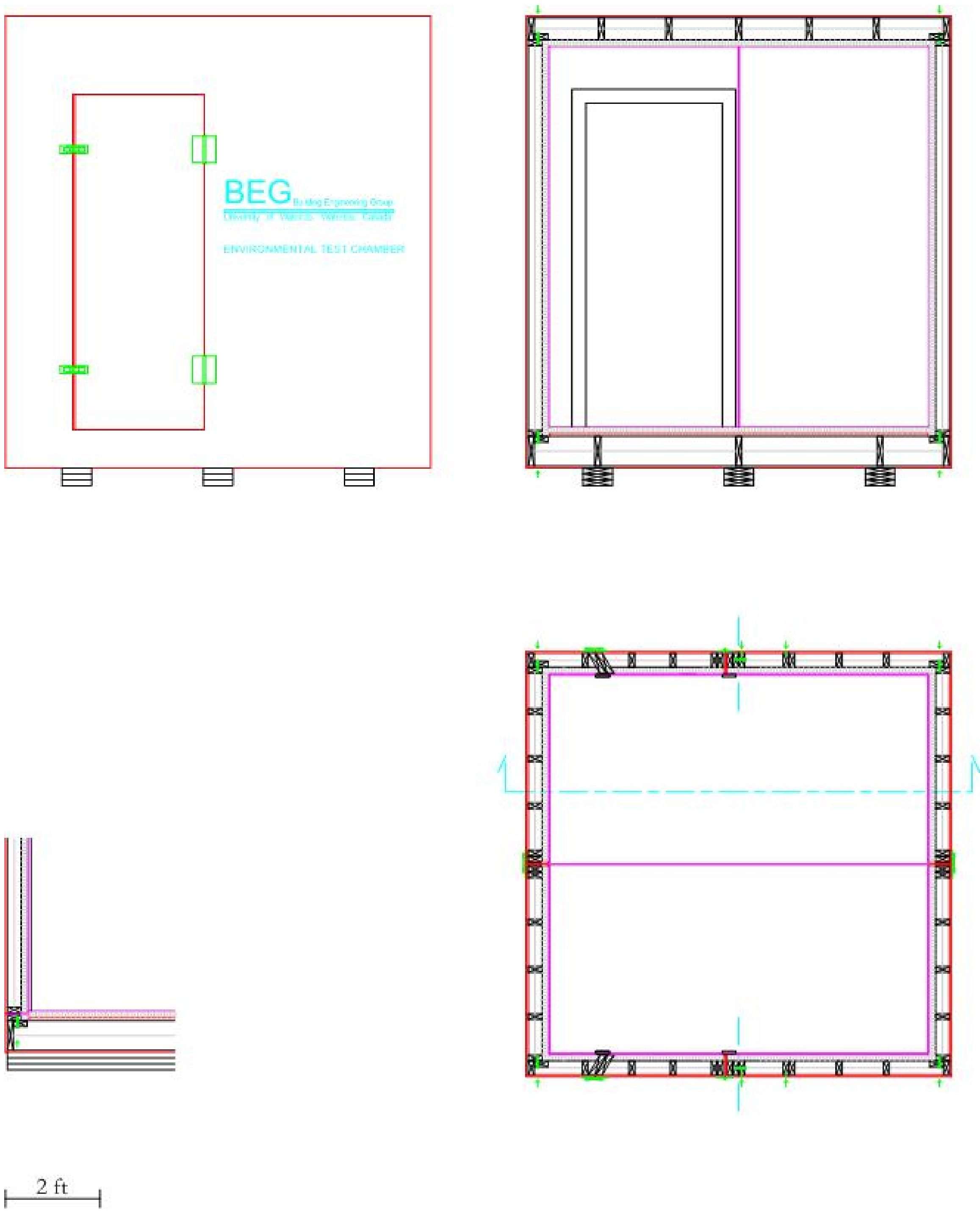
Appendix A: Climate Chamber



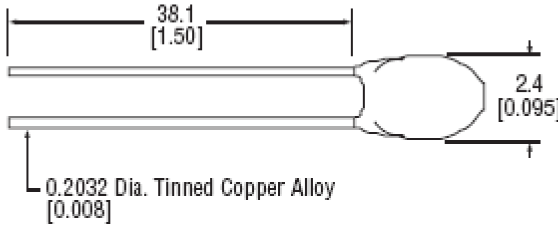


Painted G1S ½" plywood exterior
Impervious plastic interior finish
2x6 frame filled with Batt
2 layers 1 inch foil-faced polyiso foam applied
on back of interior finish


BEG
ENVIRONMENTAL TEST CHAMBER
2 ft

Appendix B: Instrumentation

192 Series Unicurve®
R-T Matched Interchangeable NTC Thermistors



UNI-CURVE® INTERCHANGEABLE THERMISTORS are high quality, low cost resistance temperature matched interchangeable thermistors. They offer additional cost savings by eliminating the need for individual resistance temperature calibration, as well as standardization of circuit components and simplification of design and replacement problems. They are particularly well suited for use in applications such as temperature measurement, indication and control. Other applications include: compensation of ambient temperature effects on copper coils, transistors, integrated circuits and other semiconductor devices.

Features

- Applications: Temperature Measurement, Indication, and Control Accuracy
- High Stability; High Reliability; Long Life
- Small Size
- Epoxy Coated; Lead Material = Tinned Copper Alloy
- Dissipation Constant = 0.75 mW/°C In Still Air Minimum
- Time Constant = 15 Sec. In Still Air Maximum
- Resistance Range = 1K Ohm to 100K Ohm
- Maximum Temperature = 150°C

Stock No.	Mfr.'s Type	Ohms @ 25°C	Tolerance ± °C	Resistance Ratio	EACH
254-0064	192-501DET-A01	500	0.2	6.35	**3.81**
254-0065	192-102DEW-A01	1K	1.0	6.35	**2.58**
254-0066	192-222LET-A01	2.2K	0.2	9.10	**3.81**
254-0067	192-222LEV-A01	2.2K	0.5	9.10	**3.13**
254-0068	192-302LET-A01	3K	0.2	9.10	**2.47**
254-0069	192-502LET-A01	5K	0.2	9.10	**3.81**
254-0070	192-103LET-A01	10K	0.2	9.10	**3.81**
254-0071	192-103LEV-A01	10K	0.5	9.10	**3.13**
254-0072	192-103LEW-A01	10K	1.0	9.10	**2.58**
254-0073	192-103LFW-A01	10K	1.0	9.10	**2.58**
254-0074	192-303KET-A01	30K	0.2	8.72	**3.81**
254-0076	192-303QET-A01	30K	0.2	8.72	**3.81**
254-0075	192-303KET-A02	30K	0.2	8.72	**3.81**
254-0077	192-503QET-A01	50K	0.2	8.72	**3.81**
254-0078	192-104QET-A01	100K	0.2	8.72	**3.81**

Fenwal Uni-Curve Series 10k Thermistor — 192-103LET-A01

Note: These sensors formerly manufactured by Fenwal, now mfr under Honeywell — Sensor Accuracy = +/- 0.2°C

Old Curve Fit: Temp = $-0.101(\mathrm{LnR})^3 + 4.346(\mathrm{LnR})^2 - 77.18(\mathrm{LnR}) + 446.05$ (in °C) — Curve fit accuracy over range of -20 to 60°C = +/- 0.12°C

New Curve Fit: Temp = $-0.0937(\mathrm{LnR})^3 + 4.143(\mathrm{LnR})^2 - 75.31(\mathrm{LnR}) + 440.385$ (in °C) — Curve fit accuracy over range of -20 to 60°C = +/- 0.03°C

Interactive Temp Calculator Using Straube's Eqn

Rmeas (Ohm)	Vmeas (V)	Vsup (V)	Rsense (Ohm)	Rmeas (Ohm)	Ln(Res)	Temp (°C)
	1.00	2.50	10,000	15,000	9.6158	15.9

Enter Measured Resistance OR Measured Voltage, Voltage Supply and Sense Resistor

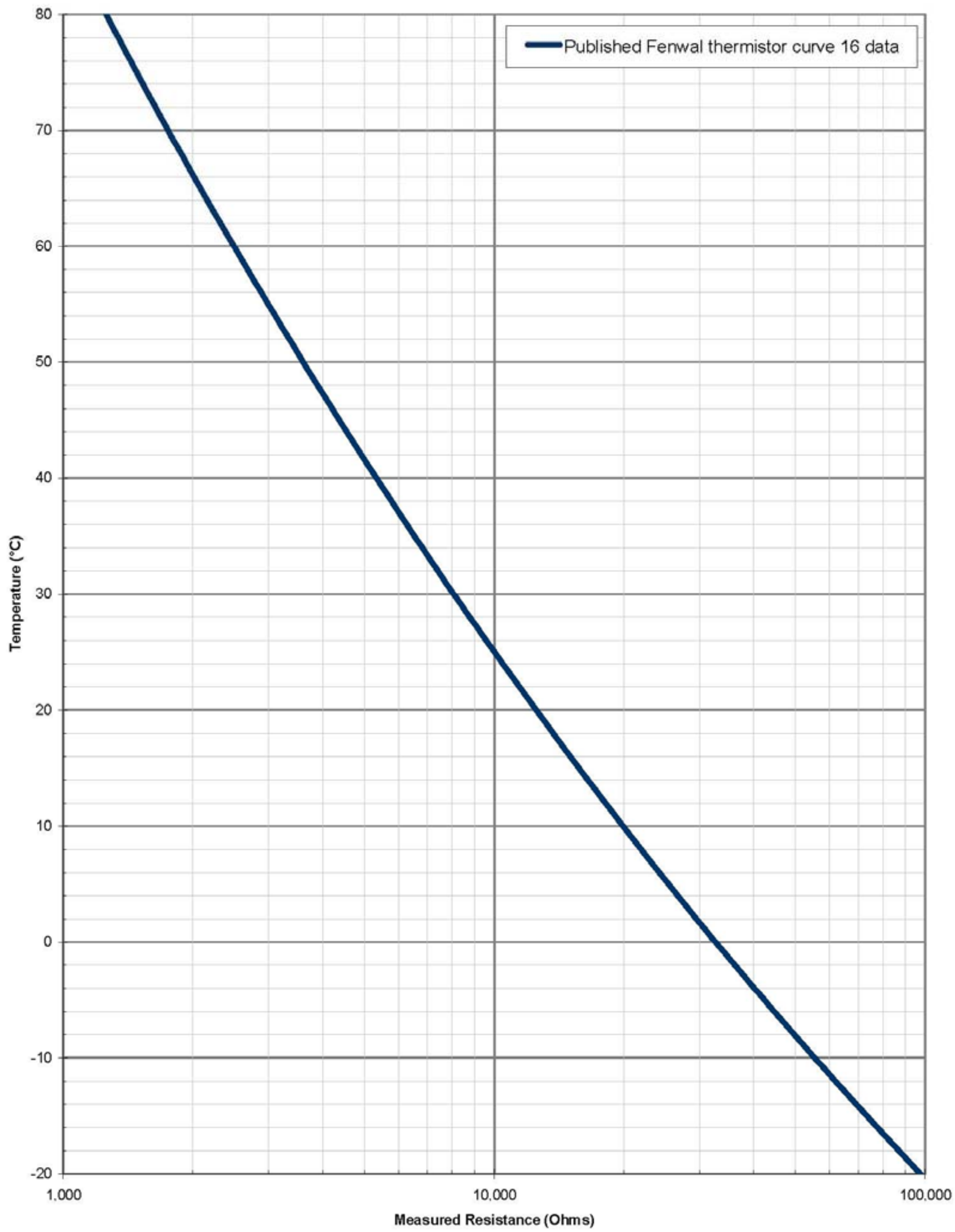
Published Fenwal thermistor curve 16 data — can't find this on Honeywell version of Fenwal site, but was on old Fenwal site

Temp	Res	Temp	Res	Temp	Res	Temp	Res	Temp	Res	Temp	Res
-50	670,100	-25	130,630	0	32,613	25	10,000	50	3,605	75	1,482
-49	623,682	-24	123,070	1	30,996	26	9,571	51	3,471	76	1,433
-48	580,809	-23	115,991	2	29,469	27	9,163	52	3,343	77	1,387
-47	541,260	-22	109,358	3	28,026	28	8,774	53	3,220	78	1,342
-46	504,665	-21	103,141	4	26,664	29	8,405	54	3,101	79	1,299
-45	470,830	-20	97,313	5	25,375	30	8,053	55	2,988	80	1,258
-44	439,540	-19	91,839	6	24,157	31	7,718	56	2,880	81	1,218
-43	410,529	-18	86,705	7	23,004	32	7,399	57	2,776	82	1,180
-42	383,656	-17	81,888	8	21,912	33	7,095	58	2,676	83	1,143
-41	358,723	-16	77,355	9	20,879	34	6,806	59	2,580	84	1,107
-40	335,615	-15	73,100	10	19,900	35	6,530	60	2,488	85	1,073
-39	314,145	-14	69,098	11	18,973	36	6,266	61	2,400	86	1,039
-38	294,195	-13	65,337	12	18,094	37	6,014	62	2,316	87	1,007
-37	275,646	-12	61,797	13	17,259	38	5,775	63	2,235	88	977
-36	258,390	-11	58,466	14	16,469	39	5,546	64	2,157	89	947
-35	242,329	-10	55,330	15	15,719	40	5,327	65	2,083	90	918
-34	227,358	-9	52,391	16	15,007	41	5,118	66	2,011	91	890
-33	213,433	-8	49,626	17	14,331	42	4,919	67	1,943	92	864
-32	200,440	-7	47,026	18	13,689	43	4,728	68	1,877	93	838
-31	188,315	-6	44,581	19	13,079	44	4,545	69	1,813	94	813
-30	176,998	-5	42,280	20	12,500	45	4,371	70	1,752	95	789
-29	166,434	-4	40,110	21	11,948	46	4,204	71	1,694	96	766
-28	156,562	-3	38,068	22	11,425	47	4,045	72	1,638	97	743
-27	147,337	-2	36,142	23	10,926	48	3,892	73	1,584	98	721
-26	138,704	-1	34,327	24	10,451	49	3,745	74	1,532	99	700
-25	130,630	0	32,613	25	10,000	50	3,605	75	1,482	100	680

Measured Resistance (Ohms) vs Temperature Readings Using New Curve Fit (2004)

Temp	Res	Temp	Res	Temp	Res	Temp	Res	Temp	Res	Temp	Res
-50	646,555	-25	130,458	0	32,639	25	9,999	50	3,607	75	1,478
-49	604,295	-24	122,902	1	31,017	26	9,572	51	3,473	76	1,429
-48	564,936	-23	115,825	2	29,485	27	9,165	52	3,344	77	1,383
-47	528,276	-22	109,195	3	28,038	28	8,778	53	3,222	78	1,337
-46	494,125	-21	102,981	4	26,670	29	8,409	54	3,103	79	1,294
-45	462,306	-20	97,155	5	25,377	30	8,058	55	2,990	80	1,252
-44	432,658	-19	91,692	6	24,155	31	7,724	56	2,882	81	1,212
-43	405,027	-18	86,567	7	22,998	32	7,406	57	2,777	82	1,173
-42	379,272	-17	81,758	8	21,904	33	7,102	58	2,678	83	1,135
-41	355,261	-16	77,243	9	20,867	34	6,812	59	2,582	84	1,100
-40	332,872	-15	73,004	10	19,887	35	6,536	60	2,491	85	1,065
-39	311,991	-14	69,021	11	18,958	36	6,272	61	2,403	86	1,031
-38	292,512	-13	65,280	12	18,077	37	6,020	62	2,318	87	999
-37	274,338	-12	61,762	13	17,243	38	5,780	63	2,237	88	968
-36	257,376	-11	58,455	14	16,452	39	5,551	64	2,159	89	938
-35	241,544	-10	55,344	15	15,702	40	5,332	65	2,084	90	909
-34	226,761	-9	52,417	16	14,990	41	5,122	66	2,012	91	881
-33	212,955	-8	49,662	17	14,315	42	4,922	67	1,943	92	854
-32	200,058	-7	47,067	18	13,674	43	4,731	68	1,877	93	828
-31	188,007	-6	44,624	19	13,065	44	4,548	69	1,813	94	802
-30	176,743	-5	42,322	20	12,487	45	4,373	70	1,752	95	778
-29	166,211	-4	40,153	21	11,938	46	4,206	71	1,693	96	755
-28	156,363	-3	38,107	22	11,416	47	4,047	72	1,635	97	732
-27	147,150	-2	36,177	23	10,919	48	3,894	73	1,581	98	711
-26	138,528	-1	34,357	24	10,448	49	3,748	74	1,529	99	689
-25	130,458	0	32,639	25	9,999	50	3,607	75	1,478	100	669

Temperature vs Measured Resistance for Fenwal Uni-Curve Series 10k Thermistor



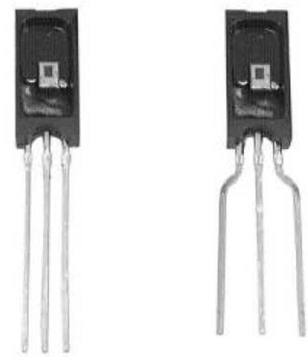
Honeywell

Humidity Sensors
Humidity Sensor

HIH-3610 Series

FEATURES
- Molded thermoset plastic housing with cover
- Linear voltage output vs %RH
- Laser trimmed interchangeability
- Low power design
- High accuracy
- Fast response time
- Stable, low drift performance
- Chemically resistant

TYPICAL APPLICATIONS
- Refrigeration
- Drying
- Metrology
- Battery-powered systems
- OEM assemblies



The HIH-3610 Series humidity sensor is designed specifically for high volume OEM (Original Equipment Manufacturer) users. Direct input to a controller or other device is made possible by this sensor's linear voltage output. With a typical current draw of only 200 µA, the HIH-3610 Series is ideally suited for low drain, battery operated systems. Tight sensor interchangeability reduces or eliminates OEM production calibration costs. Individual sensor calibration data is available.

The HIH-3610 Series delivers instrumentation-quality RH (Relative Humidity) sensing performance in a low cost, solderable SIP (Single In-line Package). Available in two lead spacing configurations, the RH sensor is a laser trimmed thermoset polymer capacitive sensing element with on-chip integrated signal conditioning. The sensing element's multilayer construction provides excellent resistance to application hazards such as wetting, dust, dirt, oils, and common environmental chemicals.

⚠WARNING
PERSONAL INJURY
- DO NOT USE these products as safety or emergency stop devices, or in any other application where failure of the product could result in personal injury.

Failure to comply with these instructions could result in death or serious injury.

⚠WARNING
MISUSE OF DOCUMENTATION
- The information presented in this product sheet is for reference only. Do not use this document as system installation information
- Complete installation, operation, and maintenance information is provided in the instructions supplied with each product.

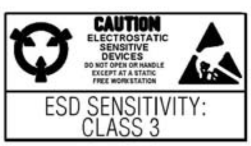
Failure to comply with these instructions could result in death or serious injury.

TABLE 1: PERFORMANCE SPECIFICATIONS

Parameter	Condition
RH Accuracy[1]	±2% RH, 0-100% RH non-condensing, 25 °C, V_{supply} = 5 Vdc
RH Interchangeability	±5% RH, 0-60% RH; ±8% @ 90% RH typical
RH Linearity	±0.5% RH typical
RH Hysteresis	±1.2% RH span maximum
RH Repeatability	±0.5% RH
RH Response Time, 1/e	15 sec in slowly moving air at 25 °C
RH Stability	±1% RH typical at 50% RH in 5 years
Power Requirements Voltage Supply Current Supply	 4 Vdc to 5.8 Vdc, sensor calibrated at 5 Vdc 200 µA at 5 Vdc
Voltage Output V_{supply} = 5 Vdc Drive Limits	V_{out} = V_{supply} (0.0062(Sensor RH) + 0.16), typical @ 25 °C (Data printout option provides a similar, but sensor specific, equation at 25 °C.) 0.8 Vdc to 3.9 Vdc output @ 25 °C typical Push/pull symmetric; 50 µA typical, 20 µA minimum, 100 µA maximum Turn-on ≤ 0.1 sec
Temperature Compensation Effect @ 0% RH Effect @ 100% RH	True RH = (Sensor RH)/(1.093-0.0021T), T in °F True RH = (Sensor RH)/(1.0546-0.00216T), T in °C ±0.007 %RH/°C (negligible) -0.22% RH/°C (<1% RH effect typical in occupied space systems above 15 °C (59 °F))
Humidity Range Operating Storage	 0 to 100% RH, non-condensing[1] 0 to 90% RH, non-condensing
Temperature Range Operating Storage	 -40 °C to 85 °C (-40 °F to 185 °F) -51 °C to 125 °C (-60 °F to 257 °F)
Package[2]	Three pin, solderable SIP in molded thermoset plastic housing with thermoplastic cover
Handling	Static sensitive diode protected to 15 kV maximum

Notes:

1. Extended exposure to ≥90% RH causes a reversible shift of 3% RH.
2. This sensor is light sensitive. For best results, shield the sensor from bright light.



FACTORY CALIBRATION

HIH-3610 sensors may be ordered with a calibration and data printout (Table 2). See order guide on back page.

TABLE 2: EXAMPLE DATA PRINTOUT

Model	HIH-3610-001
Channel	92
Wafer	030996M
MRP	337313
Calculated values at 5 V V_{out} @ 0% RH V_{out} @ 75.3% RH	 0.958 V 3.268 V
Linear output for 2% RH accuracy @ 25 °C Zero offset Slope RH	 0.958 V 30.680 mV/%RH (V_{out}-zero offset)/slope (V_{out}-0.958)/0.0307
Ratiometric response for 0 to 100% RH V_{out}	 V_{supply} (0.1915 to 0.8130)

FIGURE 1: RH SENSOR CONSTRUCTION

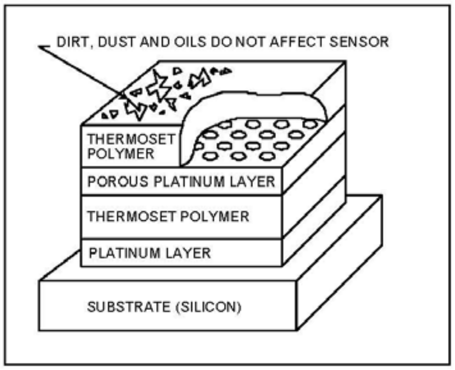


FIGURE 2: OUTPUT VOLTAGE VS RELATIVE HUMIDITY AT 0 °C

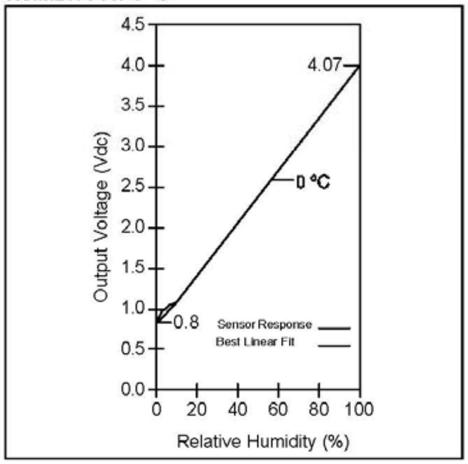
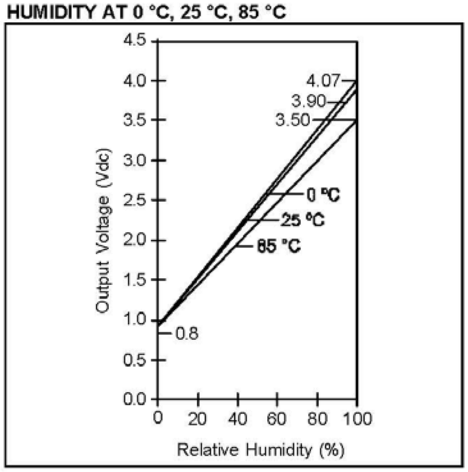


FIGURE 3: OUTPUT VOLTAGE VS RELATIVE HUMIDITY AT 0 °C, 25 °C, 85 °C



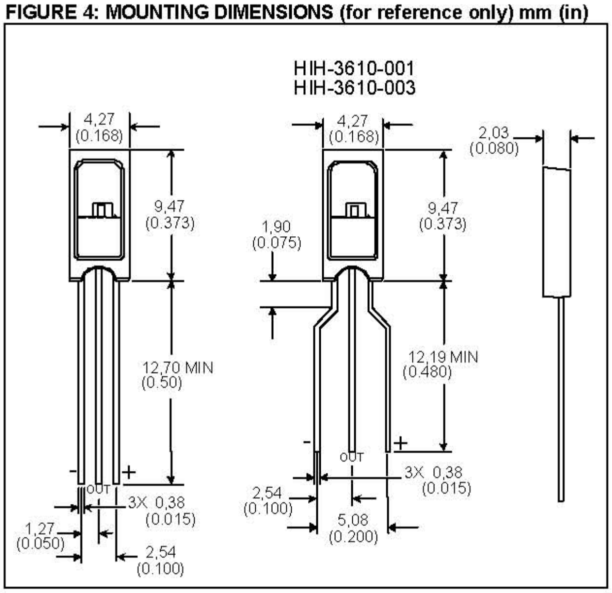
Humidity/Moisture Sensors

Humidity Sensor *HIH-3610 Series*

ORDER GUIDE

Catalog Listing	Description
HIH-3610-001	Integrated circuit humidity sensor, 0.100 in lead pitch SIP
HIH-3610-002	Integrated circuit humidity sensor, 0.050 in lead pitch SIP
HIH-3610-003	Integrated circuit humidity sensor, 0.100 in lead pitch SIP with calibration and data printout
HIH-3610-004	Integrated circuit humidity sensor, 0.050 in lead pitch SIP with calibration and data printout

FIGURE 4: MOUNTING DIMENSIONS (for reference only) mm (in)



WARRANTY/REMEDY

Honeywell warrants goods of its manufacture as being free of defective materials and faulty workmanship. Contact your local sales office for warranty information. If warranted goods are returned to Honeywell during the period of coverage, Honeywell will repair or replace without charge those items it finds defective. The foregoing is Buyer's sole remedy and is **in lieu of all other warranties, expressed or implied, including those of merchantability and fitness for a particular purpose.**

Specifications may change without notice. The information we supply is believed to be accurate and reliable as of this printing. However, we assume no responsibility for its use.

While we provide application assistance personally, through our literature and the Honeywell web site, it is up to the customer to determine the suitability of the product in the application.

For application assistance, current specifications, or name of the nearest Authorized Distributor, check the Honeywell web site or call:
1-800-537-6945 USA
1-800-737-3360 Canada
1-815-235-6847 International
FAX
1-815-235-6545 USA
INTERNET
www.honeywell.com/sensing
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Honeywell HIH 3610 series RH sensor

HIH-3610-003

Note: These sensors formerly manufactured by Hycal

Measured RH = (Vout - Zero Offset)/Slope

Accuracy = +/- 3% for Generic calibration coeffs, +/- 2% for NIST coeffs

Interactive RH Calculator

Generic		NIST		Vmeas	Voltage Divider		Vout	Measured	Vsup	Temp	RHcrctd for
Zero Offset	**Slope**	**Zero Offset**	**Slope**	(V)	**Rs (ohm)**	**R2 (ohm)**	(V)	**RH**	(V)	(°C)	**T & V**
0.958	0.03068			1.25	121,000	121,000	2.50	50.26	5.00	25.0	50.23

Either **enter NIST Zero Offset & Slope** or **accept Generic coeffs**. Enter Vout, Voltage divider info, Vsup & Temp.

Uncorrected Relative Humidity Readings vs Output Voltage (Vout)

RH Assuming Vsup = 5.0 & T = 25°C

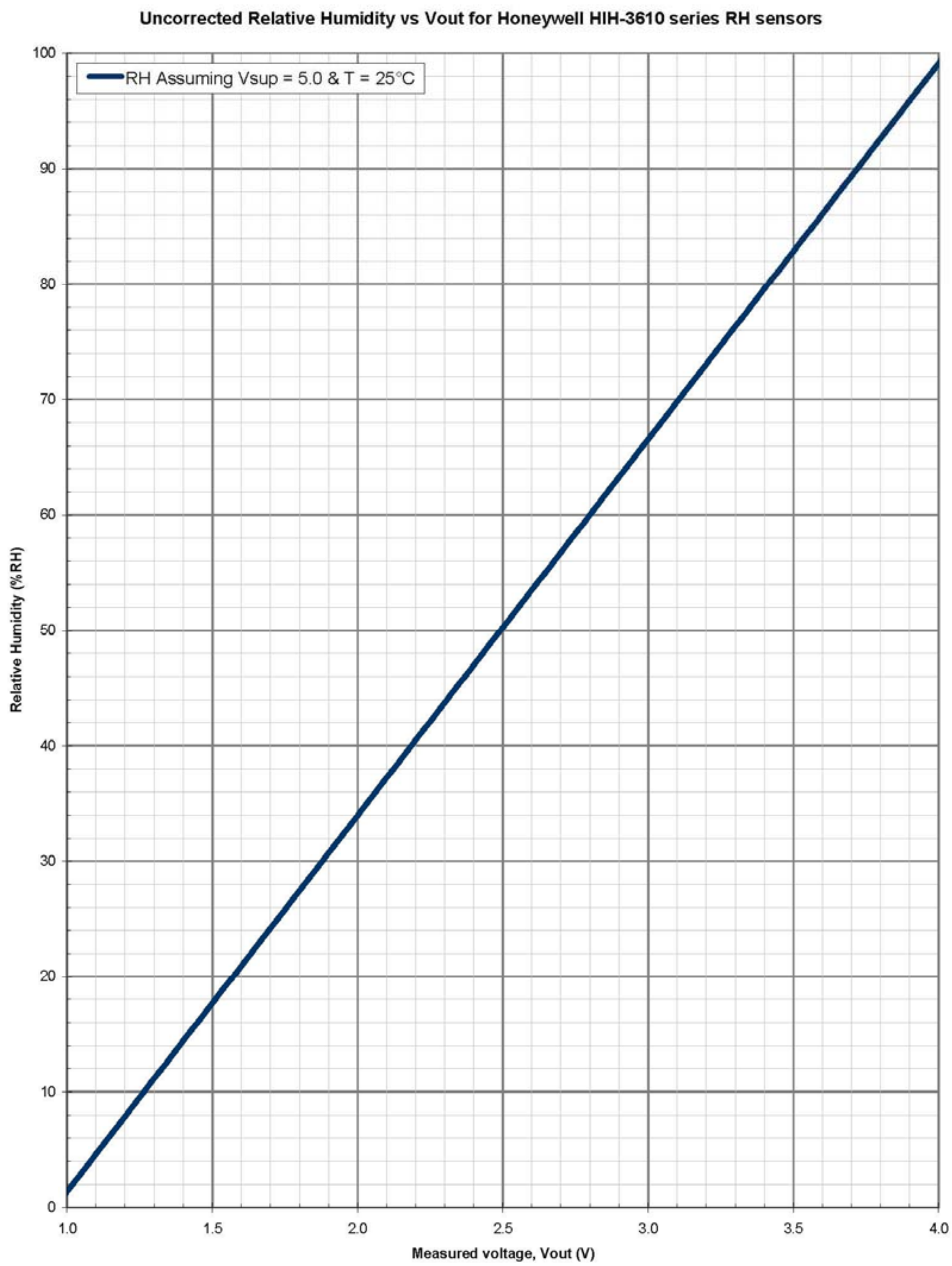
RH	Vout	RH	Vout	RH	Vout	RH	Vout	RH	Vout
1	0.989	21	1.60	41	2.22	61	2.83	81	3.44
2	1.02	22	1.63	42	2.25	62	2.86	82	3.47
3	1.05	23	1.66	43	2.28	63	2.89	83	3.50
4	1.08	24	1.69	44	2.31	64	2.92	84	3.54
5	1.11	25	1.73	45	2.34	65	2.95	85	3.57
6	1.14	26	1.76	46	2.37	66	2.98	86	3.60
7	1.17	27	1.79	47	2.40	67	3.01	87	3.63
8	1.20	28	1.82	48	2.43	68	3.04	88	3.66
9	1.23	29	1.85	49	2.46	69	3.07	89	3.69
10	1.26	30	1.88	50	2.49	70	3.11	90	3.72
11	1.30	31	1.91	51	2.52	71	3.14	91	3.75
12	1.33	32	1.94	52	2.55	72	3.17	92	3.78
13	1.36	33	1.97	53	2.58	73	3.20	93	3.81
14	1.39	34	2.00	54	2.61	74	3.23	94	3.84
15	1.42	35	2.03	55	2.65	75	3.26	95	3.87
16	1.45	36	2.06	56	2.68	76	3.29	96	3.90
17	1.48	37	2.09	57	2.71	77	3.32	97	3.93
18	1.51	38	2.12	58	2.74	78	3.35	98	3.96
19	1.54	39	2.15	59	2.77	79	3.38	99	4.00
20	1.57	40	2.19	60	2.80	80	3.41	100	4.03

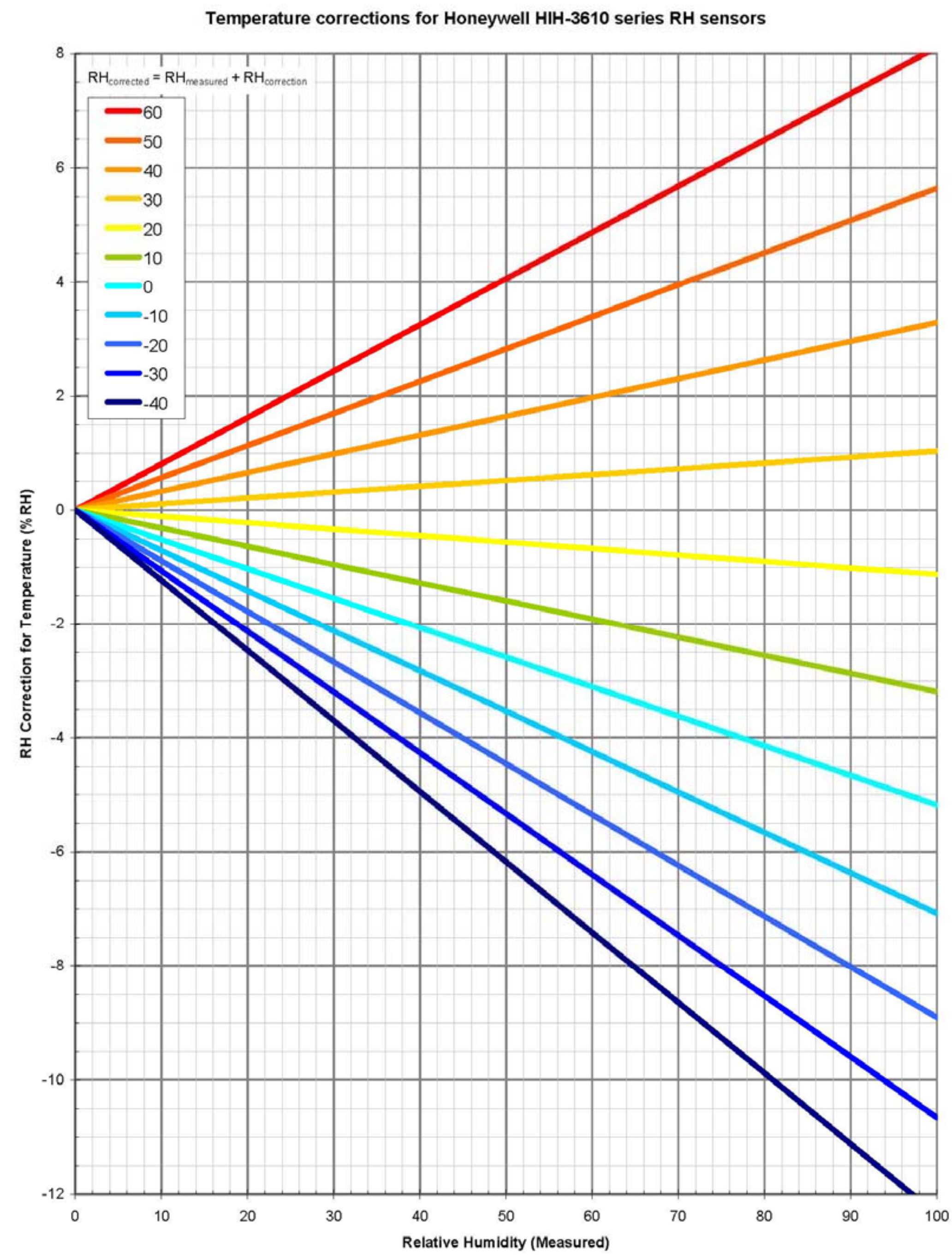
Note: For Campbell Scientific CR10x
Mult and Offset are calculated for each RH sensor using the NIST calibration coefficients specific to that sensor
Recall Generic equation (+/-3%): RH = (Vout - 0.958)/0.03068
with Vout measured across a 1:1 voltage divider
Mult = (1*2/1000)/(0.03068) = 0.065189
Offset = (-0.958)/(0.03068) = -31.22555

Temperature corrections for Honeywell HIH 3610 series RH sensors

True RH = (Sensor RH)/(1.0546-0.00216T), T in °C
RHcorrected = RHmeasured + RHcorrection

	Relative Humidity (%)										
Temp (°C)	0	10	20	30	40	50	60	70	80	90	100
-40	0.0	-1.2	-2.5	-3.7	-4.9	-6.2	-7.4	-8.7	-9.9	-11.1	-12.4
-30	0.0	-1.1	-2.1	-3.2	-4.3	-5.3	-6.4	-7.5	-8.5	-9.6	-10.7
-20	0.0	-0.9	-1.8	-2.7	-3.6	-4.5	-5.3	-6.2	-7.1	-8.0	-8.9
-10	0.0	-0.7	-1.4	-2.1	-2.8	-3.5	-4.2	-5.0	-5.7	-6.4	-7.1
0	0.0	-0.5	-1.0	-1.6	-2.1	-2.6	-3.1	-3.6	-4.1	-4.7	-5.2
10	0.0	-0.3	-0.6	-1.0	-1.3	-1.6	-1.9	-2.2	-2.6	-2.9	-3.2
20	0.0	-0.1	-0.2	-0.3	-0.5	-0.6	-0.7	-0.8	-0.9	-1.0	-1.1
30	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
40	0.0	0.3	0.7	1.0	1.3	1.6	2.0	2.3	2.6	3.0	3.3
50	0.0	0.6	1.1	1.7	2.3	2.8	3.4	3.9	4.5	5.1	5.6
60	0.0	0.8	1.6	2.4	3.2	4.1	4.9	5.7	6.5	7.3	8.1


Uncorrected Relative Humidity vs Vout for Honeywell HIH-3610 series RH sensors
RH Assuming Vsup = 5.0 & T = 25°C
Relative Humidity (% RH)
Measured voltage, Vout (V)
0
10
20
30
40
50
60
70
80
90
100
1.0
1.5
2.0
2.5
3.0
3.5
4.0



Temperature corrections for Honeywell HIH-3610 series RH sensors
$RH_{corrected} = RH_{measured} + RH_{correction}$
60
50
40
30
20
10
0
-10
-20
-30
-40
RH Correction for Temperature (% RH)
Relative Humidity (Measured)

Temperature and Relative Humidity Probe
Model HMP50

The HMP50, manufactured by Vaisala, measures air temperature with a 1000 ohm platinum resistance thermometer (PRT), and RH with the INTERCAP® capacitive chip. The chip is field-replaceable, as needed, and eliminates the downtime typically required for the recalibration process.

Sensor Mounts

When exposed to sunlight, the HMP50 must be housed in a 41030-5A 6-plate radiation shield. To attach the 41303-5A to a CM202, CM204, or CM206 crossarm, place the 41303-5A's u-bolt in the bottom holes. To attach the radiation shield directly to a tripod mast, tower mast, or tower leg, place the u-bolt in the side holes.

Ordering Information

HMP50-L	Temperature and RH Probe with user-specified lead length. Enter the lead length, in feet, after the -L. For example, HMP50-L6 orders a 6 ft lead length.
-GM	41303-5A 6-Plate Gill Radiation Shield
9598	Replacement chip for the HMP50.

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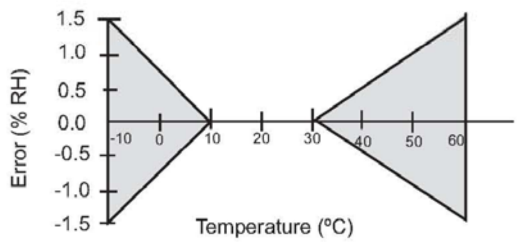
Specifications

Relative Humidity

Operating Range: 0 to 98% RH

Accuracy: 0-90% range: ±3.0%
90-98% range: ±5.0%

Temperature Dependence of Relative Humidity Measurement:

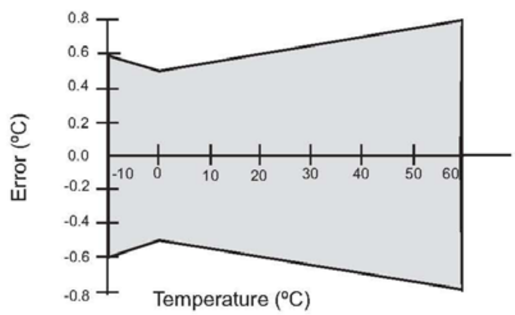


Typical Long-Term Stability: Better than ±1% RH per year

Temperature

Measurement Range: -25° to +60°C

Temperature Accuracy:



General

Supply Voltage: 7 to 28 Vdc (typically powered by datalogger's 12 V supply)

Current Consumption: 2 mA typical

Diameter: 0.47" (1.2 cm)

Length: 2.8" (7.1 cm)

Housing Material: chrome-coated aluminum and chrome-coated ABS plastic

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CR10X Specifications

Electrical specifications are valid over a -25° to +50°C range unless otherwise specified; non-condensing environment required. To maintain electrical specifications, Campbell Scientific recommends recalibrating dataloggers every two years.

PROGRAM EXECUTION RATE

Program is synchronized with real-time up to 64 Hz. One channel can be measured at this rate with uninterrupted data transfer. Burst measurements up to 750 Hz are possible over short intervals.

ANALOG INPUTS

NUMBER OF CHANNELS: 6 differential or 12 single-ended, individually configured. Channel expansion provided by AM16/32 or AM416 Relay Multiplexers and AM25T Thermocouple Multiplexers.

ACCURACY: ±0.1% of FSR (-25° to 50°C);
±0.05% of FSR (0° to 40°C);
e.g., ±0.1% FSR = ±5.0 mV for ±2500 mV range

RANGE AND RESOLUTION:

Full Scale Input Range (mV)	Resolution (µV) Differential	Single-Ended
±2500	333	666
±250	33.3	66.6
±25	3.33	6.66
±7.5	1.00	2.00
±2.5	0.33	0.66

INPUT SAMPLE RATES: Includes the measurement time and conversion to engineering units. The fast and slow measurements integrate the signal for 0.25 and 2.72 ms, respectively. Differential measurements incorporate two integrations with reversed input polarities to reduce thermal offset and common mode errors.

Fast single-ended voltage:	2.6 ms
Fast differential voltage:	4.2 ms
Slow single-ended voltage:	5.1 ms
Slow differential voltage:	9.2 ms
Differential with 60 Hz rejection:	25.9 ms
Fast differential thermocouple:	8.6 ms

INPUT NOISE VOLTAGE (for ±2.5 mV range):
Fast differential: 0.82 µV rms
Slow differential: 0.25 µV rms
Differential with 60 Hz rejection: 0.18 µV rms

COMMON MODE RANGE: ±2.5 V

DC COMMON MODE REJECTION: >140 dB

NORMAL MODE REJECTION: 70 dB (60 Hz with slow differential measurement)

INPUT CURRENT: ±9 nA maximum

INPUT RESISTANCE: 20 Gohms typical

ANALOG OUTPUTS

DESCRIPTION: 3 switched, active only during measurement, one at a time.

RANGE: ±2.5 V

RESOLUTION: 0.67 mV

ACCURACY: ±5 mV; ±2.5 mV (0° to 40°C)

CURRENT SOURCING: 25 mA

CURRENT SINKING: 25 mA

FREQUENCY SWEEP FUNCTION: The switched outputs provide a programmable swept frequency, 0 to 2.5 V square wave for exciting vibrating wire transducers.

RESISTANCE MEASUREMENTS

MEASUREMENT TYPES: The CR10X provides ratiometric bridge measurements of 4- and 6-wire full bridge, and 2-, 3-, and 4-wire half bridges. Precise dual polarity excitation using any of the switched outputs eliminates dc errors. Conductivity measurements use a dual polarity 0.75 ms excitation to minimize polarization errors.

ACCURACY: ±0.02% of FSR plus bridge resistor error.

PERIOD AVERAGING MEASUREMENTS

The average period for a single cycle is determined by measuring the duration of a specified number of cycles. Any of the 12 single-ended analog input channels can be used. Signal attentuation and ac coupling are typically required.

INPUT FREQUENCY RANGE:

Signal peak-to-peak[1] Min.	Max.	Min. Pulse w.	Max Freq.[2]
500 mV	5.0 V	2.5 µs	200 kHz
10 mV	2.0 V	10 µs	50 kHz
5 mV	2.0 V	62 µs	8 kHz
2 mV	2.0 V	100 µs	5 kHz

[1]Signals centered around datalogger ground
[2]Assuming 50% duty cycle

RESOLUTION: 35 ns divided by the number of cycles measured

ACCURACY: ±0.01% of reading (number of cycles ≥100)
±0.03% of reading (number of cycles <100)

TIME REQUIRED FOR MEASUREMENT: Signal period times the number of cycles measured plus 1.5 cycles + 2 ms

PULSE COUNTERS

NUMBER OF PULSE COUNTER CHANNELS: 2 eight-bit or 1 sixteen-bit; software selectable as switch closure, high frequency pulse, and low level ac.

MAXIMUM COUNT RATE: 16 kHz, eight-bit counter; 400 kHz, sixteen-bit counter. Channels are scanned at 8 or 64 Hz (software selectable).

SWITCH CLOSURE MODE
Minimum Switch Closed Time: 5 ms
Minimum Switch Open Time: 6 ms
Maximum Bounce Time: 1 ms open without being counted

HIGH FREQUENCY PULSE MODE
Minimum Pulse Width: 1.2 µs
Maximum Input Frequency: 400 kHz
Voltage Thresholds: Count upon transition from below 1.5 V to above 3.5 V at low frequencies. Larger input transitions are required at high frequencies because of input filter with 1.2 µs time constant. Signals up to 400 kHz will be counted if centered around +2.5 V with deviations ≥ ±2.5 V for ≥ 1.2 µs.
Maximum Input Voltage: ±20 V

LOW LEVEL AC MODE
(Typical of magnetic pulse flow transducers or other low voltage, sine wave outputs.)

Input Hysteresis: 14 mV

Maximum ac Input Voltage: ±20 V

Minimum ac Input Voltage:

(Sine wave mV RMS)	Range (Hz)
20	1.0 to 1000
200	0.5 to 10,000
1000	0.3 to 16,000

DIGITAL I/O PORTS

8 ports, software selectable as binary inputs or control outputs. 3 ports can be configured to count switch closures up to 40 Hz.

OUTPUT VOLTAGES (no load): high 5.0 V ±0.1 V; low < 0.1 V

OUTPUT RESISTANCE: 500 ohms

INPUT STATE: high 3.0 to 5.5 V; low -0.5 to 0.8 V

INPUT RESISTANCE: 100 kohms

SDI-12 INTERFACE STANDARD

Digital I/O Ports C1-C8 support SDI-12 asynchronous communication; up to ten SDI-12 sensors can be connected to each port. Meets SDI-12 Standard version 1.2 for datalogger and sensor modes.

CR10XTCR THERMOCOUPLE REFERENCE

POLYNOMIAL LINEARIZATION ERROR: Typically <±0.5°C (-35° to +50°C), <±0.1°C (-24° to +45°C).

INTERCHANGEABILITY ERROR: Typically <±0.2°C (0° to +60°C) increasing to ±0.4°C (at -35°C).

CE COMPLIANCE (as of 09/01)

STANDARD(S) TO WHICH CONFORMITY IS DECLARED:
EN55022: 1995 and EN61326: 1998

EMI and ESD PROTECTION

IMMUNITY: Meets or exceeds following standards:
ESD: per IEC 1000-4-2; ±8 kV air, ±4 kV contact discharge
RF: per IEC 1000-4-3; 3 V/m, 80-1000 MHz
EFT: per IEC 1000-4-4; 1 kV power, 500 V I/O
Surge: per IEC 1000-4-5; 1 kV power and I/O
Conducted: per IEC 1000-4-6; 3 V 150 kHz-80 MHz

Emissions and immunity performance criteria available on request.

CPU AND INTERFACE

PROCESSOR: Hitachi 6303

PROGRAM STORAGE: Up to 16 kbytes for active program; additional 16 kbytes for alternate programs. Operating system stored in 128 kbytes Flash memory.

DATA STORAGE: 128 kbytes SRAM standard (approximately 60,000 data values). Additional 2 Mbytes Flash available as an option.

OPTIONAL KEYBOARD DISPLAY: 8-digit LCD (0.5" digits)

PERIPHERAL INTERFACE: 9 pin D-type connector for keyboard display, storage module, modem, printer, card storage module, and RS-232 adapter.

BAUD RATES: Selectable at 300, 1200, 9600 and 76,800 bps for synchronous devices. ASCII communication protocol is one start bit, one stop bit, eight data bits (no parity).

CLOCK ACCURACY: ±1 minute per month

SYSTEM POWER REQUIREMENTS

VOLTAGE: 9.6 to 16 Vdc

TYPICAL CURRENT DRAIN: 1.3 mA quiescent, 13 mA during processing, and 46 mA during analog measurement.

BATTERIES: Any 12 V battery can be connected as a primary power source. Several power supply options are available from Campbell Scientific. The Model CR2430 lithium battery for clock and SRAM backup has a capacity of 270 mAhr.

PHYSICAL SPECIFICATIONS

SIZE: 7.8" x 3.5" x 1.5" - Measurement & Control Module; 9" x 3.5" x 2.9" - with CR10WP Wiring Panel. Additional clearance required for serial cable and sensor leads.

WEIGHT: 2 lbs

WARRANTY

Three years against defects in materials and workmanship.

We recommend that you confirm system configuration and critical specifications with Campbell Scientific before purchase.

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Appendix C: Borate Concentration Analysis

Internal: Various wood samples

Seventy-two samples were received 2/02/04.

Samples were leached for 1 hour in 1.0 N HCl.

* Note: OSB samples corrected for 5 % moisture content.

sample bottle/	T.T #	Sample I.D.		Sample WEIGHT	Dry WEIGHT *	LEACHATE WEIGHT	ICP ppm B	% B	% BAE (B)	% ZB (B)	ICP ppm Zn	% Zn	% BAE (Zn)	% ZB (Zn)	B/Zn (ZB)
00	00	T Newberry STD		4.00		100.64	60.2	0.15	0.87	1.02					
1	1	UT-Ply A	X	9.70		100.03	4.4	0.00	0.03	0.03					
2	2	UT-Ply A	Y	8.47		100.46	4.0	0.00	0.03	0.03					
3	3	UT-Ply A	Z	7.98		100.48	3.9	0.00	0.03	0.03					
4	4	UT-Ply B	X	7.71		100.65	5.5	0.01	0.04	0.05					
5	5	UT-Ply B	Y	7.57		100.42	5.7	0.01	0.04	0.05					
6	6	UT-Ply B	Z	6.94		100.70	5.0	0.01	0.04	0.05					
7	7	UT-Ply C	X	10.41		100.64	6.5	0.01	0.04	0.04					
8	8	UT-Ply C	Y	8.69		100.46	5.4	0.01	0.04	0.04					
9	9	UT-Ply C	Z	6.94		99.04	5.2	0.01	0.04	0.05					
10	10	UT-OSB A	X	7.79	7.40	99.96	1.0	0.00	0.01	0.01	1.1	0.00	0.00	0.00	1.83
11	11	UT-OSB A	Y	7.06	6.71	100.69	0.7	0.00	0.01	0.01	1.3	0.00	0.01	0.01	1.08
12	12	UT-OSB A	Z	8.21	7.80	99.74	0.9	0.00	0.01	0.01	1.7	0.00	0.01	0.01	1.07
13	13	UT-OSB B	X	9.22	8.76	100.71	1.2	0.00	0.01	0.01	1.3	0.00	0.00	0.00	1.86
14	14	UT-OSB B	Y	7.88	7.49	100.76	0.0	0.00	0.00	0.00	1.0	0.00	0.00	0.00	0.00
15	15	UT-OSB B	Z	8.49	8.07	100.57	0.0	0.00	0.00	0.00	1.1	0.00	0.00	0.00	0.00
16	16	UT-OSB C	X	8.05	7.65	100.61	0.0	0.00	0.00	0.00	1.0	0.00	0.00	0.00	0.00
17	17	UT-OSB C	Y	7.25	6.89	100.58	0.0	0.00	0.00	0.00	0.9	0.00	0.00	0.00	0.00
18	18	UT-OSB C	Z	7.46	7.09	100.53	0.0	0.00	0.00	0.00	1.0	0.00	0.00	0.00	0.00
19	19	T-Ply A	X	8.30		100.62	212.6	0.26	1.47	1.73					
20	20	T-Ply A	Y	7.71		100.47	218.1	0.28	1.62	1.91					
21	21	T-Ply A	Z	6.90		100.59	180.0	0.26	1.50	1.76					
22	22	T-Ply B	X	10.31		100.67	256.3	0.25	1.43	1.68					
23	23	T-Ply B	Y	7.19		100.63	171.9	0.24	1.37	1.61					
24	24	T-Ply B	Z	7.71		100.66	187.0	0.24	1.40	1.64					
25	25	T-Ply C	X	9.12		99.67	232.9	0.25	1.45	1.71					
26	26	T-Ply C	Y	8.23		100.16	206.4	0.25	1.44	1.69					
27	27	T-Ply C	Z	9.54		99.68	216.9	0.23	1.30	1.52					
28	28	T-OSB A	X	9.84	9.35	99.90	134.3	0.14	0.82	0.96	289.4	0.31	0.88	1.03	0.93
29	29	T-OSB A	Y	10.14	9.63	100.30	144.0	0.15	0.86	1.01	306.2	0.32	0.91	1.06	0.95
30	30	T-OSB A	Z	9.61	9.13	100.20	134.8	0.15	0.85	0.99	285.3	0.31	0.89	1.04	0.95
31	31	T-OSB B	X	8.48	8.06	100.25	131.4	0.16	0.93	1.10	275.4	0.34	0.98	1.14	0.96
32	32	T-OSB B	Y	8.45	8.03	99.86	131.3	0.16	0.93	1.10	273.4	0.34	0.97	1.13	0.97
33	33	T-OSB B	Z	8.43	8.01	100.11	133.8	0.17	0.96	1.12	281.3	0.35	1.00	1.17	0.96
34	34	T-OSB C	X	7.91	7.51	99.78	120.2	0.16	0.91	1.07	252.3	0.34	0.95	1.12	0.96
35	35	T-OSB C	Y	8.80	8.36	100.13	122.4	0.15	0.84	0.98	259.0	0.31	0.88	1.03	0.95
36	36	T-OSB C	Z	8.49	8.07	100.23	125.1	0.16	0.89	1.04	262.8	0.33	0.93	1.09	0.96
37	37	UN-SPF	X	15.65		150.19	3.2	0.00	0.02	0.02	0.0				
38	38	UN-SPF	Y	15.17		150.97	1.5	0.00	0.01	0.01	0.0				
39	39	UN-SPF	Z	14.86		150.25	1.3	0.00	0.01	0.01	0.0				
40	40	UN-SPF Core	X	2.16		99.79	0.0	0.00	0.00	0.00	0.0				
41	41	UN-SPF Core	Y	2.10		100.49	0.0	0.00	0.00	0.00	0.0				
42	42	UN-SPF Core	Z	2.05		100.49	0.0	0.00	0.00	0.00	0.0				
43	43	UN-SYP	X	19.55		149.86	5.5	0.00	0.02	0.03	0.0				
44	44	UN-SYP	Y	19.11		149.89	2.7	0.00	0.01	0.01	0.0				
45	45	UN-SYP	Z	19.57		150.05	2.8	0.00	0.01	0.01	0.0				
46	46	UN-SYP Core	X	2.12		99.64	0.0	0.00	0.00	0.00	0.0				
47	47	UN-SYP Core	Y	2.33		99.90	0.0	0.00	0.00	0.00	0.0				
48	48	UN-SYP Core	Z	2.13		99.58	0.0	0.00	0.00	0.00	0.0				
49	49	UT- DFIR	X	18.00		150.45	2.1	0.00	0.01	0.01	0.0				
50	50	UT- DFIR	Y	17.59		149.83	1.6	0.00	0.01	0.01	0.0				
51	51	UT- DFIR	Z	17.61		150.90	1.9	0.00	0.01	0.01	0.0				
52	52	UT- DFIR Core	X	2.72		100.43	0.0	0.00	0.00	0.00	0.0				
53	53	UT- DFIR Core	Y	2.60		100.45	0.0	0.00	0.00	0.00	0.0				
54	54	UT- DFIR Core	Z	2.69		100.25	0.0	0.00	0.00	0.00	0.0				
55	55	T-SPF	X	17.22		150.93	474.0	0.42	2.37	2.79	0.0				
56	56	T-SPF	Y	17.12		150.65	458.9	0.40	2.31	2.71	0.0				
57	57	T-SPF	Z	17.81		150.80	428.2	0.36	2.07	2.43	0.0				
58	58	T-SPF Core	X	2.36		100.67	3.0	0.01	0.07	0.09	0.0				
59	59	T-SPF Core	Y	2.34		100.46	2.5	0.01	0.06	0.07	0.0				
60	60	T-SPF Core	Z	2.50		100.54	3.2	0.01	0.07	0.09	0.0				
61	61	T-SYP	X	16.17		150.70	807.1	0.75	4.30	5.05	0.0				
62	62	T-SYP	Y	15.60		151.68	805.9	0.78	4.48	5.26	0.0				
63	63	T-SYP	Z	15.84		150.80	949.1	0.90	5.16	6.06	0.0				
64	64	T-SYP Core	X	2.08		100.36	107.2	0.52	2.96	3.47	0.0				
65	65	T-SYP Core	Y	2.12		100.30	105.7	0.50	2.86	3.36	0.0				
66	66	T-SYP Core	Z	2.29		100.40	106.7	0.47	2.67	3.14	0.0				
67	67	T-DFIR	X	18.86		150.37	1043.0	0.83	4.75	5.58	0.0				
68	68	T-DFIR	Y	18.23		150.65	933.6	0.77	4.41	5.18	0.0				
69	69	T-DFIR	Z	18.49		151.04	906.0	0.74	4.23	4.97	0.0				
70	70	T-DFIR Core	X	2.54		100.38	81.6	0.32	1.84	2.16	0.0				
71	71	T-DFIR Core	Y	2.46		100.41	69.6	0.28	1.62	1.91	0.0				
72	72	T-DFIR Core	Z	2.51		100.23	60.0	0.24	1.37	1.61	0.0				
73	73	Untreated Spike		3.98	0.0465	100.42	68.3	14.75	84.28	98.99	151.9	32.80	93.46	109.35	0.91

Internal: Various wood samples

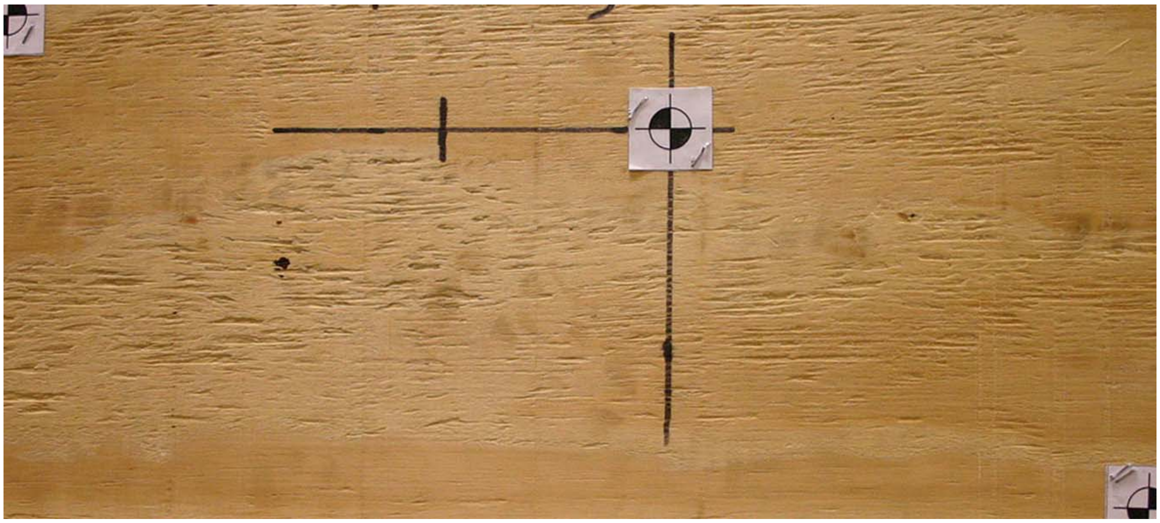
Eighteen samples were received 01/05/05.

Samples were leached for 3 hour in 1.0 N HCl.

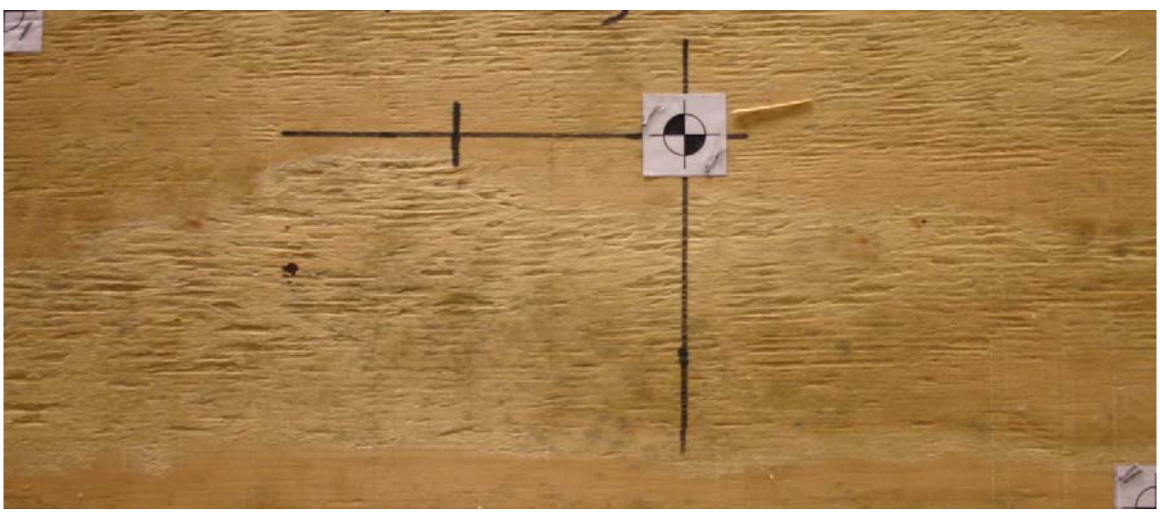
* Note: OSB samples corrected for 5 % moisture content.

sample bottle/	T.T #	Sample I.D.	Sample WEIGHT	Dry WEIGHT *	LEACHATE WEIGHT	ICP ppm B	% B	% BAE (B)	% ZB (B)	ICP ppm Zn	% Zn	% BAE (Zn)	% ZB (Zn)	B/Zn (ZB)
00	00	T Newberry STD	4.07	3.87	100.54	70.5	0.17	1.00	1.17	142.0	0.37	1.05	1.23	0.95
1	1	T-OSB-A-1	4.00	3.80	100.58	60.4	0.15	0.87	1.02	128.2	0.34	0.97	1.13	0.90
2	2	T-OSB-A-2	4.22	4.01	100.77	77.3	0.18	1.05	1.24	149.9	0.38	1.07	1.26	0.99
3	3	T-OSB-A-3	4.11	3.90	100.49	73.7	0.18	1.03	1.21	144.4	0.37	1.06	1.24	0.98
4	4	T-OSB-B-1	4.18	3.97	100.54	64.7	0.16	0.89	1.04	126.8	0.32	0.91	1.07	0.98
5	5	T-OSB-B-2	4.00	3.80	100.69	59.2	0.15	0.85	1.00	119.9	0.32	0.91	1.06	0.94
6	6	T-OSB-B-3	4.05	3.85	100.73	57.9	0.14	0.82	0.97	115.3	0.30	0.86	1.01	0.96
7	7	T-OSB-C-1	4.02	3.82	100.50	62.2	0.16	0.89	1.04	125.7	0.33	0.94	1.10	0.95
8	8	T-OSB-C-2	4.30	4.09	100.71	62.9	0.15	0.84	0.99	127.8	0.32	0.90	1.05	0.94
9	9	T-OSB-C-3	4.10	3.90	100.71	65.5	0.16	0.92	1.08	120.5	0.31	0.89	1.04	1.04
10	10	UT-OSB-A-1	4.14	3.93	100.43	0	0.00	0.00	0.00	0.8	0.00	0.01	0.01	0.00
11	11	UT-OSB-A-2	4.12	3.91	101.33	0	0.00	0.00	0.00	0.6	0.00	0.00	0.01	0.00
12	12	UT-OSB-A-3	3.92	3.72	100.83	0	0.00	0.00	0.00	0	0.00	0.00	0.00	-
13	13	UT-OSB-B-1	4.13	3.92	101.09	1.2	0.00	0.02	0.02	0	0.00	0.00	0.00	-
14	14	UT-OSB-B-2	4.34	4.12	100.97	0	0.00	0.00	0.00	0.6	0.00	0.00	0.00	0.00
15	15	UT-OSB-B-3	4.34	4.12	100.98	0	0.00	0.00	0.00	0.6	0.00	0.00	0.00	0.00
16	16	UT-OSB-C-1	4.33	4.11	100.89	1.2	0.00	0.02	0.02	0.6	0.00	0.00	0.00	4.03
17	17	UT-OSB-C-2	4.04	3.84	100.88	0	0.00	0.00	0.00	0	0.00	0.00	0.00	-
18	18	UT-OSB-C-3	4.15	3.94	100.65	0	0.00	0.00	0.00	0	0.00	0.00	0.00	-
19	19	UT + ZB SPIKE	4.07	3.87	100.51	63.3	0.16	0.89	1.05	131.5	0.34	0.97	1.14	0.92

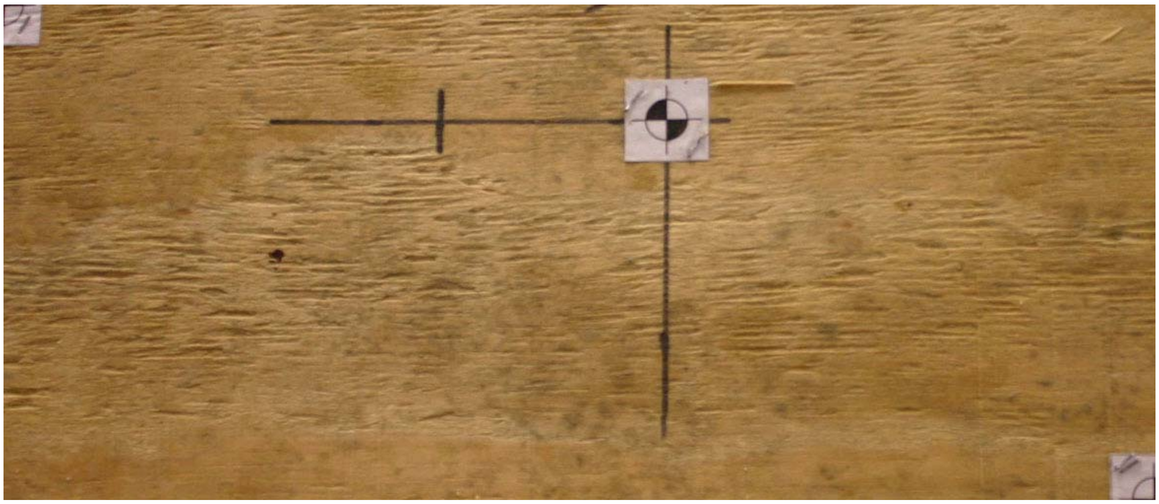
Appendix D: Visual Correlation Between Mould Index and Mould Growth



Mould Index 0 thru 2

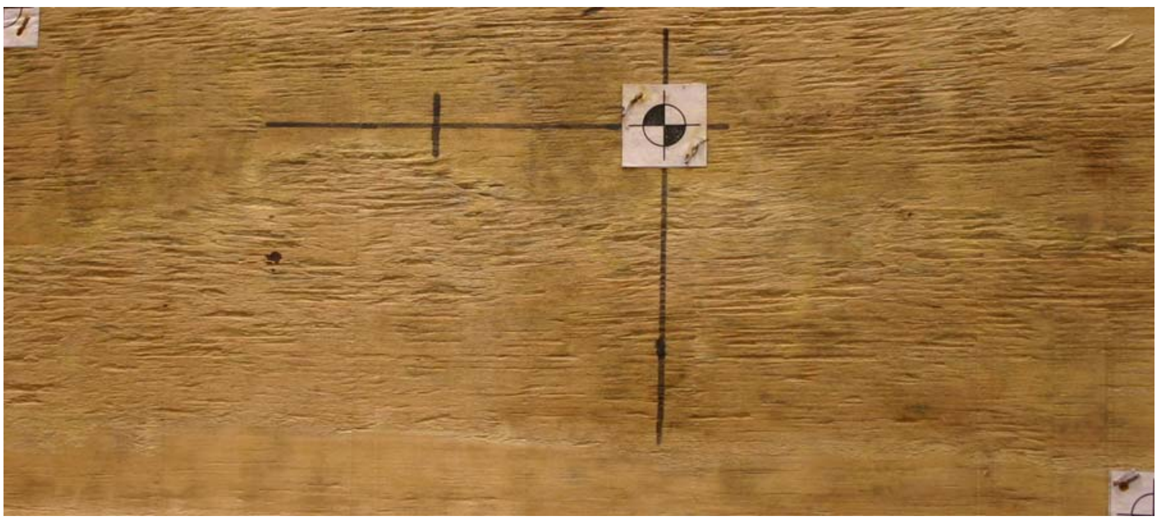


Mould Index 3



Mould Index 4

Mould Index 5



Mould Index 6